SUSPENSION CHARACTERISTICS OF PARTICULATE SOLIDS IN STIRRED TANKS

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In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By

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C E R T I F I C A T E

Certified that the present work 'SUSPENSION CHARACTERISTICS OF PARTICULATE SOLIDS IN STIRRED TANKS' has been carried out under my supervision and the work has not been submitted elsewhere for a degree.

January, 24, 1979
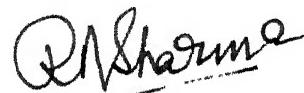
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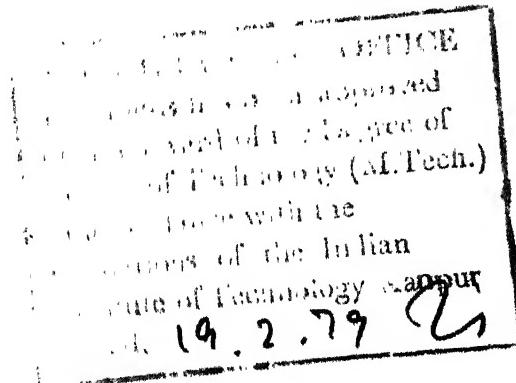
A C K N O W L E D G E M E N T

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NOMENCLATURE

A =   Constant for a given physical system, defined in equation 4.3

B =   Weight of the solid particles in suspension, per weight of liquid, times 100 percent

C =   Distance between the stirrer and the bottom of the vessel (cm)

D =   Diameter of stirrer (cm)

D_p =   Size of the solid particle (cm)

H =   Height of the liquid in vessel (cm)

H_{sl} =   Net hydrostatic head of the slurry (cm of water)

g =   Accelaration due to gravity (cm/sec^2)

g_c =   Gravitational conversion factor $\left(980.66 \ \dfrac{gm_m \ cm}{gm_f \ sec^2} \right.$

N =   Rotational speed of stirrer (r.p.m.)

N_c =   Critical speed of suspension at which no particle remains on the vessel bottom (r.p.s.)

P =   Power input (gm cm/sec)

R =   Weight ratio of solid to liquid i.e. gms of solid/ gms of liquid

S =   Dimensionless form, from equation 4.1

S' =   A, variable defined in equation 4.2

T =   Vessel diameter (cm)

t =   Constant exponent of (T/D) term in equation 1

v =   Volume of the stirred liquid charge (cm^3)

ρ_s = Density of solid particle (gm/cm^3)

ρ_1 = Density of liquid (gm/cm^3)

μ = Viscosity of liquid $(gm/cm\ sec)$

ν = μ/ρ_ℓ (cm^2/sec)

ψ = Constant

Suspension of solid particles in liquids is an important aspect of many chemical process industries. Generally, the particulate solid suspensions are accomplished in a tank charged with a liquid by rotation an impeller. The minimum speed of rotation at which all the solid particles are just suspended is termed as the critical speed of suspension (N_c).

There have been many empirical and semi-empirical studies conducted to obtain correlations which would predict N_c-values for known stirred systems. The results of many such studies do not agr not agree and there is a fair amount of diversity for N_c-values calculated from each one of them for a specified system.

The most successful relation widely used in industry is the one proposed by Zwietering. It is based on a large number of experiments and in a simplified form can be represented, for a centrally mounted mixer rotating in a flat bottom cylindrical tank containing liquid and particulate solids, as

$$A \ N_c \ D^{0.85} = (T/D)^t$$

where D and T are the impeller diameter and tank diameter respectively and A is a function of the physical properties of particulate system.

It should be noted that observations for N_c were made visually and therefore could be viewed as subjective.

The present study was undertaken to test other methods of measuring N_c and to obtain more information on 'A' and 't'

Two other methods one by physically withdrawing the local suspension in sampling system and the other by light-scattering technique were employed to measure N_c-values, which were also obtained visually. All the three methods give almost identical values of N_c. Thus, the simpler method of visual observation is validated.

The data shows the value of exponent on B to be 0.13. It also shows that N_c varies as $1/D^{0.84}$. Both of them are in excellent agreement with corresponding values proposed by Zwietering.

is shown to be a function of type of stirrer and not on the dimension and position of the stirrer in the tank. 't' however, depends both on the type of impeller and on its position in the tank. Quantitative relations have been proposed relating 't' to the ratio of tank diameter to its clearance from the tank bottom (T/C) for the two types of mixers employed in the present study i.e. square pitch marine propeller and six flat blade paddle impeller.

CHAPTER-1

INTRODUCTION

1.1 General

Many chemical processes involve suspension of solid particles in liquids, e.g. leaching and washing of crushed ore, salt dissolution and crystalizations, dispersion of nuclear fuel (thoria-urania) in water for feeding in to reactor and extraction of organic infusion in the dye industry. The objective of these processes is to achieve the maximum dispersion of solid in liquid phase. The agitated vessel often reffered as stirred tank, is most frequently used in chemical process industry to bring about an excellent solid liquid contact.

When the solid particles are charged in the liquid phase, the particles settle down because of higher density. To lift these solid particles from the bottom of the vessel and suspend in the liquid, it is essential to supply energy which will work against the gravity, drag and buoyant-forces. This is usually accomplished through the rotation of impeller.

The impeller speed at which all the particulate solids just become fully suspended is an important parameter because at this stage the total surface area of particles is most efficiently utilized for the process like mass transfer, etc. Above this speed the rate of such processes as dissolution increases slowly. While the power dissipation increases remarkably.

Essentially two main suspension states can be defined as:
(i) Complete suspension, which could be defined as the agitated state of the vessel charge where no solids remained at the bottom for longer than 1 or 2 seconds i.e. all the solids are just suspended and the corresponding rotational speed of impeller is termed as the critical speed of suspension (N_c).
(ii) Uniform suspension, where in the particulate solids are uniformaly distributed throughout the liquid in the stirred tank charge i.e. the local concentration of solids is same or nearly same everywhere in the agitated liquid region.

The present study primarily concern with the suspension and not the subsequent homogenization step.

LITERATURE REVIEW

1.2

Because of complex hydrodynomical nature of two phase turbulent flow in a stirred tank, theoretical approach to the problem of suspension is very difficult. There is, as yet, no completely satisfactory method for predicting solids suspension characteristics in agitated vessels, although a considerable amount of attention both in terms of empirical and semi-empirical studies, has been given to this intractable problem in recent years.

It has long been recognised, for example, that the impeller geometry and speed coupled with vessel geometry and physical

properties of the particulate system, are the important parameters, which determine critical speed of suspension. Empirical corelations are based on this concept. Semi-empirical correlations assume a model of suspension followed by analysis. The studies have been reported in terms of minimum power needed to suspend the particle or directly as N_c, out of several studies that have been made to determine the critical speed of suspension with a variety of solids, liquids and impellers in baffled and unbaffled vessels, following are some of the typical expressions reported on the basis of these studies.

Experiments were conducted by Zwietering (1) in fully baffled transparent vessel with sand and sodium chloride as particulate solids dispersed in a variety of liquids e.g. water, acetone, carbontetra chloride, potassium corbonate solution and oil. Paddles flat blade turbines, vaned discs and propellers each of different diameter were the agitators used. The data was correlated by the following empirical expression.

$$N_c = \psi (T/D)^t \frac{g^{0.45} (\rho_s - \rho_l)^{0.45} \mu^{0.1} D_p^{0.2} (B)^{0.13}}{\rho_l^{0.55} D^{0.85}} \quad \ldots 1.1$$

Where
N_c = stirrer speed   rev/sec
T = vessel diameter   cm
D = stirrer diameter   cm
g = acceleration due to gravity   cm/sec^2
ρ_s = density of the solid   gm/cm^3
ρ_l = density of the liquid   gm/cm^3
μ = viscosity of the liquid   gm/cm sec
D_p = particle size of the solid   cm
B = weight of the solid in suspension, per weight of liquid, times 100   percent
ψ = constant
t = constant

ψ and t have values dependent on the type of stirrer and its clearance from the bottom.

Investigations were carried out by Pavlushenko et al. (2) with dispersed particulate solids as sand and iron in different liquids stirred in unbaffled vessels with three blade square pitch propellers. The data was correlated by the following expression:

$$N_c = 0.105 \; \frac{g^{0.6} \; \rho_s^{0.8} \; D_p^{0.4} \; T^{1.9}}{\mu^{0.2} \; \rho_\ell^{0.6} \; D^{2.5}} \quad \ldots 1.2$$

Basically, the experiments were performed by Kneule (3), to study the rate of solution of crystals in stirred vessels. It was observed that below the fully suspended state i.e. for impeller speeds less than N_c, the total area of the particulate solids available for dissolution was not efficiently utilized and above this speed whole of the available area is already exposed and the rate of dissolution increases rather slowly. The critical speed of suspension is therefore, important on the basis of experiments, directed to determine N_c, the expression reported in terms of power input to the stirrer is:

$$P = \frac{Ak \; (B)^{0.5} \; v \; g^{1.5} \; (\rho_s - \rho_\ell)^{1.5} \; D_p^{0.5}}{\rho_s^{0.5}} \quad \ldots 1.3$$

Where v is the volume of the stirred liquid charge.

Ak is dimensionless constant depending upon the geometry of the agitator system. The value of Ak is not given in Kneule's paper.

Kolar (4) used a semi empirical approach starting with the assumption that it is necessary to supply through the mixer just that

amount of energy which is required to maintained the solid phase in suspension i.e.

$$P = g \, V_s \, (\rho_s - \rho_\ell) U_t \qquad \qquad \dots \, 1.4$$

Where V_s is the volume of solids.

U_t is the settling velocity in the turbulent liquid.

Second assumption for the resistance of a submerged body of to motion in a fluid is:

$$\phi_t \, U_t^2 = \phi_o \, U_o^2 \qquad \qquad \dots \, 1.5$$

Where U_o is the settling velocity of the particle in liquid medium at rest. Therefore :

$$\epsilon = \frac{P}{V_1 \, \rho_\ell} = g \, \frac{V_s \, (\rho_s - \rho_\ell)}{V_1 \, \rho_\ell} \, (\phi_o/\phi_t)^{\frac{1}{2}} \, U_o \qquad \dots \, 1.6$$

The above equation can be rearranged to dimensionless form as:

$$\left(\frac{\epsilon}{g \, U_o}\right)\left(\frac{V_1}{V_s}\right)\left(\frac{\rho_1}{\rho_s - \rho_\ell}\right) = \left(\frac{\phi_o}{\phi_t}\right)^{\frac{1}{2}} \qquad \dots \, 1.7$$

With $U_t \approx ND$, equation 1.7 reduces to:

$$\left(\frac{\epsilon}{g U_o}\right) \left(\frac{V_1}{V_s}\right) \left(\frac{\rho_\ell}{\rho_s - \rho_\ell}\right) = \left(\frac{\phi_o}{\phi_1}\right)^{\frac{1}{2}} \approx \frac{ND}{U_o} \qquad \dots \, 1.8$$

Now the actual power which the mixer transmits to unit mass of liquid on attaining homogeneity of the suspension can be expressed as :

$$\epsilon_s = \gamma_1 N^3 D^2 \qquad \qquad \dots \, 1.9$$

Where γ_i is function of concentration of solids and physical and geometric properties of the system.

Thus:

$$\gamma_i(\frac{\epsilon}{\epsilon_s}) \quad (\frac{U_o^2}{g\,D}) \quad (\frac{V_1}{V_s}) \quad (\frac{\rho_1}{\rho_s - \rho_\ell})' = (\frac{ND}{U_o})^{-2} \ldots 1.10$$

The ratio (ϵ/ϵ_s) can be taken as equipment efficiency. $\gamma(\epsilon/\epsilon_s)$ can reasonably be assumed as functions of variables appearing in the above equations. Therefore;

$$\frac{N\tilde{D}}{U_o} = K \, (\frac{U_o^2}{gD})^a \quad (\frac{V_s}{V_1})^b \quad (\frac{\rho_s - \rho_\ell}{\rho_1})^c \quad (\frac{D}{T})^d \ldots 1.11$$

Kolar, on the basis of experiments, reported the values of K, a, b, c and d for square-pitch propeller, paddle with 45° slope and 6-bladed flat-turbine at specified positions of the mixer from the tank bottom. For example, for propeller with a clearance T/3 from the bottom the values of the constant and exponents, in the order mentioned, are 106.2, -0.266, 0.093, 0.112 and -1.559.

Narayan and coworkers (5) proposed a theoretical expression for N_c. The underlying assumption of this model is that at suspended state the net upward force on a single particle equals the net downward force, where from the authors obtain the following expression:

$$U = \int \{ 2g \, (\rho_s - \rho_\ell) \, (\frac{2D_P}{3\rho_1} + \frac{R \, H_{sl}}{\rho_s + R \, \rho_1}) \} \qquad \ldots 1.12$$

Where U could be taken as the minimum velocity of the fluid to suspend the particles. Now on the basis of flow pattern correspondir

to a flat blade paddle, another expression was obtained as :

$$U_z = \frac{N (D/T)^2 (2T - D)}{0.9} \quad \cdots \quad 1.13$$

Where U_z is the average fluid velocity in the flow pattern loop. On the basis of underlying assumption U should be equal to Uz.

Finally the expression for N_c is reported in the following form:

$$N_c = 1.782 (100R)^{-0.22}(\tfrac{T}{D})^2 (\tfrac{1}{2T-D})\sqrt{\left\{ 2g(\rho_s - \rho_l) \left[\frac{2D_p}{3\rho_l} + \frac{R H_{sl}}{\rho_s + R\rho_l} \right]\right\}}\cdots 1.$$

Where H_{sl} is the net hydrostatic head of the slurry.

A wide possible combination of agitated vessel geometry, impeller type, size and impeller location within the vessel were choosen for the studies in agitated wessel. The impeller was eight flat bladed paddle type and vessel was cylindrical, fully baffled and flat bottomed.

Wiesman and Efferding (6) also used the method of semi-empirical study. The equation for power to obtain a suspension interface height z' is given as:

$$\frac{1.74 \, ga \, P}{g \, V \, U_s' \, (\Delta\rho)} \left(\frac{1 - \epsilon_t}{\epsilon_t}\right) \left(\frac{D}{T}\right) = 0.16 \, e^{5.3 \, a/T} \quad \cdots 1.15$$

Where P = power to get off-bottom particle motion.
ϵ_t = liquid fraction nased on vessel volume V.
U_s' = Relative verticle velocity between particle and fluid in turbulent region
$= 1.74 (\frac{g \, D_p \, \Delta\rho}{\rho_l})^{\frac{1}{2}}$
a = clearance from the tank bottom.

A new model has been proposed for the determination of minimum stirrer speed for complete suspension by Baldi and co workers (7). he underlying principles in this analysis is that at the complete

. suspension state, the particles previously suspended drop and stop in certain zones of the tank bottom and then (after 1 or 2 seconds) are suspended again.

It can beassumed that the suspension of particles is mainly due to eddies of certain critical scale. Eddies with lower scale than the critical one do not have the energy necessary to move particles being at rest on the bottom; eddies with larger scale have frequencies less than those with the critical scale and hence have less probability to 'hit' and suspend the particles. On the basis of their assumption and experimental data they got the following expression:

$$N_c \varpropto \frac{\mu^{0.17}(\Delta\rho g)^{0.42}\ D_p^{0.12}\ B^{0.125}}{\rho_1^{0.58}\ D^{0.89}} \quad \dots\ 1.16$$

The above equation is very similar to Zwitering's relation. But the similarity is confined to the case of C/D = 1 and if C/D is changed the exponents in above equation will change.

1.3 PRESENT WORK

In all the above studies the aim of workers to determine the critical stirrer speed for suspension with different types of impeller. The N_c - values calculated from various expressions discussed above give widely different values.for a specified system. The discripancies in the N_c-values may be due to non identical experimental conditions.

For example, the clearance of the impeller from the tank bottom
is not reported whereas it is recognised that the clearance has
a marked effect on N_c. Also, baffled system has not been used
throughout. A few investigators conducted experiments without
using baffles. Each study has its own range of viscosity and
density ratio.

Despite the shortcomings in general approach for predicting
the value of N_c, the Zwietering relation has a validity based
on numerous experiments. Process industry dealing with particu-
late suspensions use the relation in situation where the critical
speed of suspension can not be measured insitu and has to be
known a priori.

In, Zwietering's relation γ and t vary with the type and
position of the stirrer. It has been observed by Uhl and
Gray (9) that γ changes from a value of 1 to 2. An average value
of 1.5 hasbeen suggested for practical use. Similarly for 't' a
value of 1.4 has been recommended. It should be noted that N_c-
values as used by Zwietering were measured visually and therefore
such a method could be viewed as purely subjective.

The basic purpose of the present study is to develop
and establish alternative experimental methods to measure
N_c- values and compare them with the values observed visually,
and subsequently   with the help of N_c- data obtained more
regorously to look more carefully at the nature and magnitude
of γ and 't'. Since various particle loadings were used the
exponent 't' on the concentration term in Zwietering relation
that is B could also be verified.

CHAPTER-2

EXPERIMENTAL EQUIPMENT

The experimental set up as shown in Fig. 2.1 consist of two parts (i) Mixing set up and (ii) Measuring equipments.

Mixing set up: It consist of glass vessel with transparent flat bottom having stainless-steel baffles, a d.c. motor along with Voltage stabilizer and variable auto-transfarmer, stirrers and stirrer shaft.

Measuring equipment: 1. Instruments to determine rotational speed of impellers.

2. Sampling device.

3. Visual observation instruments.

4. Equipments for light scattering method.

2.1 Mixing set up

Cylindrical tanks made of glass were used in the present study. The sizes are listed in table 2.1. To ensure the base of the tank as flat, a corning glass beaker of appropriate dimensions was taken. Its base was removed. The residual cylinder was then glued by Araldite to a perspex plate along the groove already cut in the plate. Three perspex slabs of equal dimensions were fixed at the bottom of the vessel for support. The stainless steel bafflesof the following dimensions were used.

Width of the baffles = 1/10 tank diameter

Length of the baffles = height of the tank

Thickness of the baffles = 1/16 inches

The stirrer shaft was made of stainless steel and the length of the shaft was kept approximately 1.5 times of the tank

Fig. 2.1 – Schematic diagram of experimental set-up.
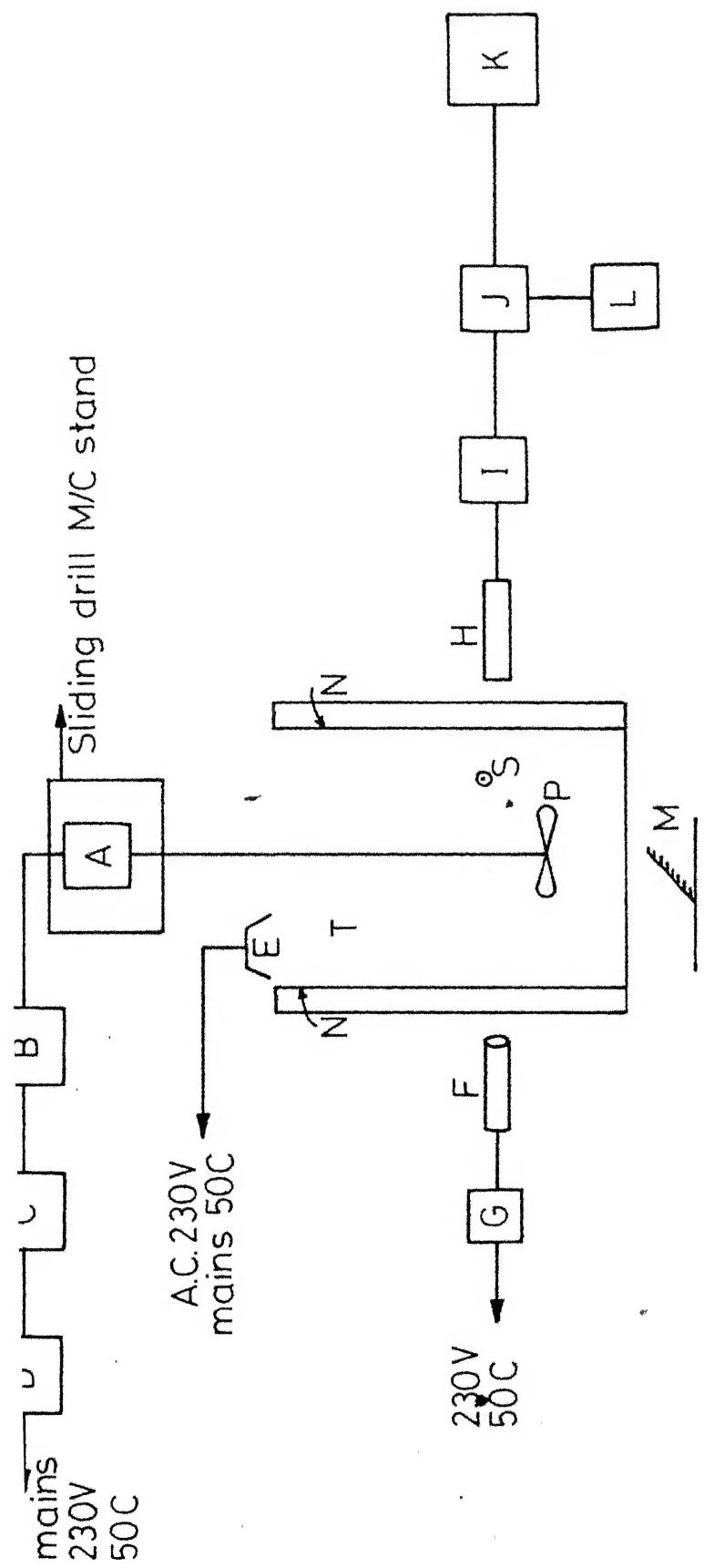
A – Motor
B – Rectifier unit
C – Variable auto transformer
D – Voltage stabilizer
E – 60W lamp
F – Microscopic lamp
G – Regulated D.C. power supply
H – Photo-multiplier tube
I – Amplifier

J – Averaging unit
K – Linear chart recorder
L – Oscilloscope
M – Plane mirror
N – Baffles
P – Propeller
T – Tank
S – Sampling point

height. The shaft was properly coupled to the motor shaft by means of screws. The outer diameter of the stirrer shaft was slightly less than the internal diameter of the impeller diameter through which shaft had to pass. To locate the centre of vessel, the free end of the stirrer shaft was made conical and by coinciding the tip of shaft to the centre point of vessel bottom it was possible to have axis of vessel and stirrer concident and types of stirrer used are listed in table 2.2.

Table 2.1   Dimensions of the vessels

1	Vessel diameter (cm)	12.75	14.07	16.20	21.7
2	Vessel volume (l)	2.00	3.00	5.00	10.0

Table 2.2   Types and dimensions of stirrers

Type of stirrer	Diameter (cm)		
Marine Propeller	–	6.00	7.80
Flat blade paddle impeller	5.1	6.38	7.65

A d.c. motor (1/15 H.P.) was mounted on a vertical sliding 'Wolf' drill machine stand. To adjust the speed of the motor a variable auto-transformer (with d.c. rectifier unit) was connected in series to a voltage stabilizer (Motawani). The level of the base of stand was adjusted in horizontal plane with the help of sprit level. Similarily the motor was mounted on the stand in such a way so that the shaft should be perpendicular to the plane of the base of stand.

2.2 Measuring equipments

2.2.1 Instruments to determine rotational speed of impellers

For determination of speed of impellers a tachometer (Ventur A.T.H. 7, British made) and a calibrated stroboscope (G.E.) flash meter were employed.

2.2.2 Sampling device:

Samples were sucked out from the agitated suspension through a sampling tube (6.0 mm I.D.) in to an evacuated round bottom flask of 100 ml capacity, having a female B-10 joint near neck with an angle about 20° to 30° with respect to vertical axis of flask. A tube of 6.00 mm and approximately 20 cm in length carrying a male joint (B-10) at its one end was fitted to this inclined neck, to suck the sample fig, 2.2.

2.2.3 Visual observation instruments:

To conduct visual observation a plane mirror was placed under the bottom of tank with an angle of 45° to the plane of bottom and tank contents were illuminated with the help of a 60 watt lamp from the top of the vessels. The bottom contents of the vessel were viewed by the above mentioned mirror.

2.2.4 Equipments for light scattering method:

In this method a photo-multiplier tube (RCL Electron tube 680 A made in U.S.A.) with an amplifier circuit, to amplify the signal generated by the photo-tube was used as detecting unit. A microscopic lamp which could slide as a unit, in the horizontal as well as vertical plane(i.e. parallel to the axis of the vessel). A regulated d.c. power supply was connected to glow the microscopic lamp (6 volt, 12 watt) to throw a constant intensity light on the tank. Lateral

6mm

Vacuum
stopcock

B-10
socket

100 ml

Sampling flask
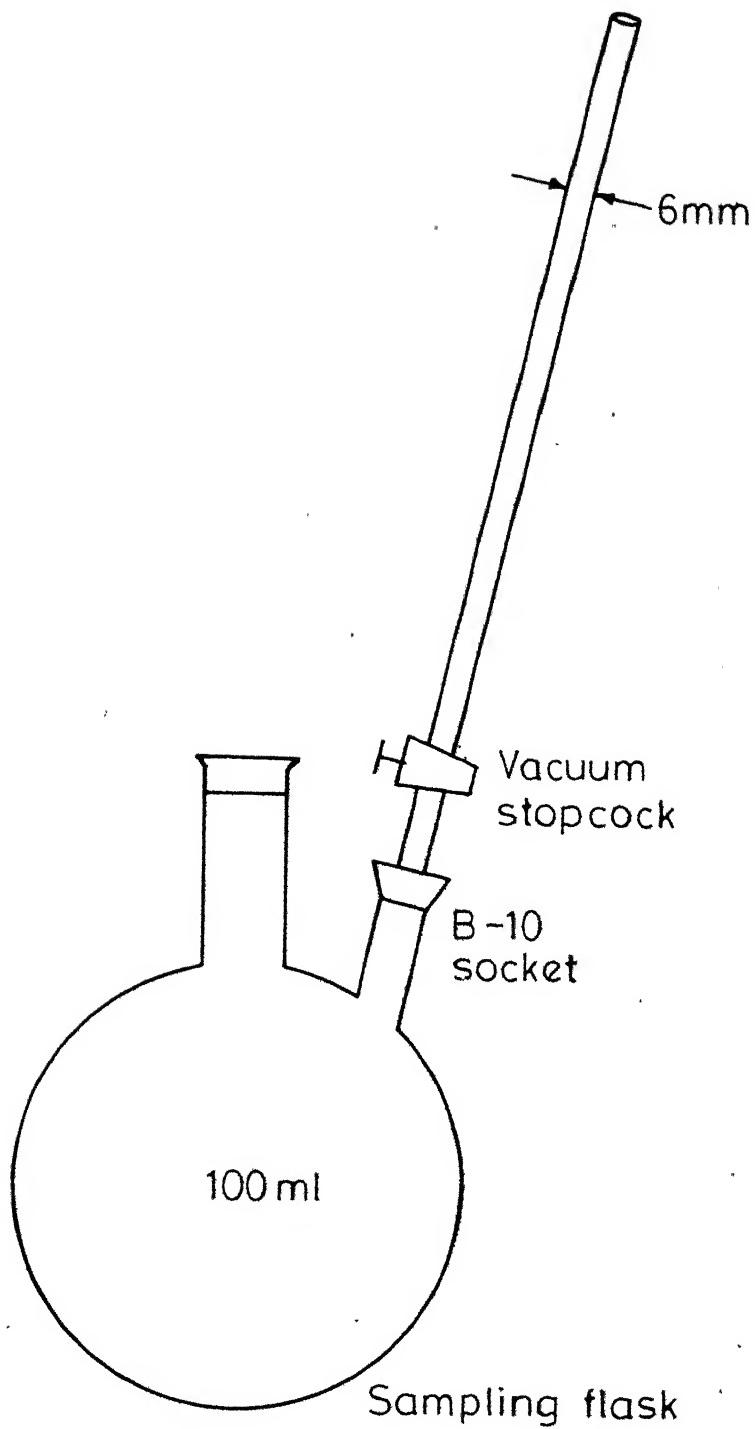
Fig. 2·2 – Sampling device.

surface of the tank was covered with a black paper except for two small openings. These openings were in one horizontal line through which a thin light beam passed. The vessel contents were illuminated at a fixed height from the tank bottom and residual transmitted light after passing through the suspension was received by the detector unit i.e. photo-multiplier. The signal generated l this unit was amplified. The fluctuations were rectified by means a linear averaging unit. Then the output of this unit was fed to an oscilloscope (OS 763, ECI Ltd., India) as well as a linear recording unit (Encardio-rite model 531 A). A schematic block diagram is shown in figure 21.

CHAPTER-3

EXPERIMENTAL PROCEDURE

Before starting an experiment it was ensured that:

1. Bottom of the tank was horizantal.

2. Stirrer shaft was vertical and

3. The axis of the stirrer shaft and vertical axis of the tank were coincident.

The first condition was met with the help of Sprit-level by adjusting the base of the stand on which vessel was placed. The second condition was fulfilled by drawing plumb line. The third condition was achieved by coinciding the tip of stirrer shaft to the centre point of vessel bottom.

Baffles were placed in the vessel in such a way that all the baffles were touching the wall and the bottom of the vessel. The height of the stirrer from the tank bottom was adjusted by moving the shaft motor assembly up or down through the lever provided in drill machine stand.

A measured amount of distilled water was poured in the vessel up to a height, 0.69 times the diameter of tank. Next, a weighbd amount of sized glass beads was charged in the tank to get the desired average tank concentration. Increase in the height of the liquid level due to solid particle was very small and hence negelected. The top vessel was covered by a perspax plate as shown in figure (3.1).

Now, the motor was started and r. p. m. of stirrer was fixed at a desired value with the help of a variable auto-transformer. The r.p.m. values were measured with tachometer and als
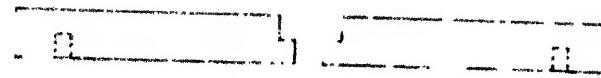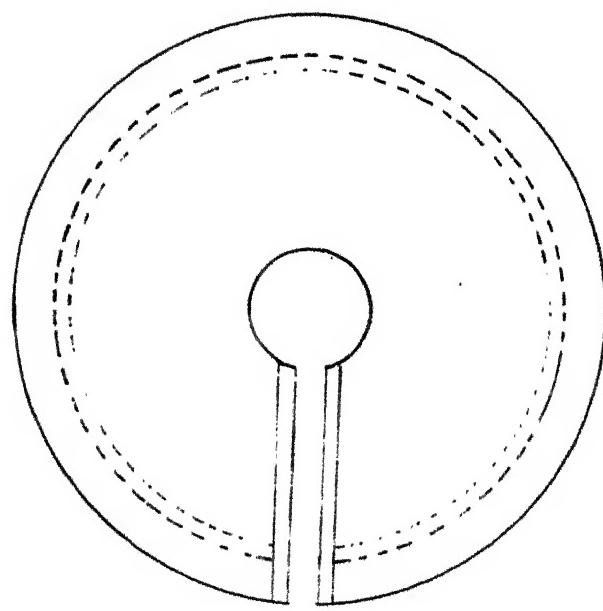
FIG. —3.1   TOP PLATE

with stroboscope. To collect local sample of the agitated slurry
the side tube of evacuuated flask was inserted in the tank throu
the hole of sliding block placed on the top plate slot (Fig. 3.1
Then vacuum stop cock was suddenly opened and closed, there by
trapping a given amount of local sample. The collected slurry
was filtered through a Sintered funnel(size G-2). Volume of the
filterate was noted and the remaining glass beads were washed wit
acetone and dried in an oven. These solid particles were weighed
The local sample concentration expressed as the ratio of the mass
of beads to the mass of liquid times 100 was known. These two
parts of the sample (glass beads and water)were then transferred
to the tank before taking the next sample. This process was
repeated four or five times to get an average concentration value
for a particular (fixed) rotational speed of the stirrer. The
above process was repeated again and average sample concentration
was found out at different rotational speed. During sampling the
conditions of with-drawing the sample were held constant i.e.
the flask was evacuuated to the same degree of vacuum and the
stem of sampling tube was positioned at the same point and the
stop cock to let the sample flow up in the evacuuated flask
was opened and closed to the same length of time. Any departure
from these conditions gave errorneous sample concentrations
because of non-isokinetic withdrawl condition.

The experiments were repeated at different solid loadings
and data were obtained in terms of sample concentrations at
different stirrer speed. From these data critical speed of
suspension was found out by plotting concentration against
stirrer speed. The rotational speed of stirrer at which sample

concentration reaches maximum was taken as critical speed of
suspension (discussed later in Results and Discussion).

These N_c values were next found out visually by means of
an inclined mirror (Fig. 2.1). In this method the criteria given
by Zwietering (1) for the critical speed of suspension, was
applied.

The N_c-values for the same set of experiments, except
for high particle-loadings were also found out by light-scatter-
ing technique. In this method the critical speed of suspension
was observed by the same criteria as used in sampling technique.
Since the decrease in intensity of transmitted light passing
through the vessel contents, was directly proportional to the
number of solid particles intersecting the light beam. Therefore,
at the critical speed of suspension the intensity of transmitted
light was minimum which was detected by photo-multiplier tube
and was looked on the screen of oscilloscope. This signal,
generated by photo-multiplier tube was recorded on a linear
chart recorder (Encardia-rite).

The several combinations of tank diameter and impeller
diameter by using propeller and flat bladed paddle impeller were
used to determine N_c-values. In most of these studies only two
methods i.e. visual method and light scattering method were
used to determine N_c-values, once it was ensured by a few
initial observation that N_c-values as determined by physically
withdrawing the sample was more or less same, as observed
visually or through light scattering technique Fig. 3.2.
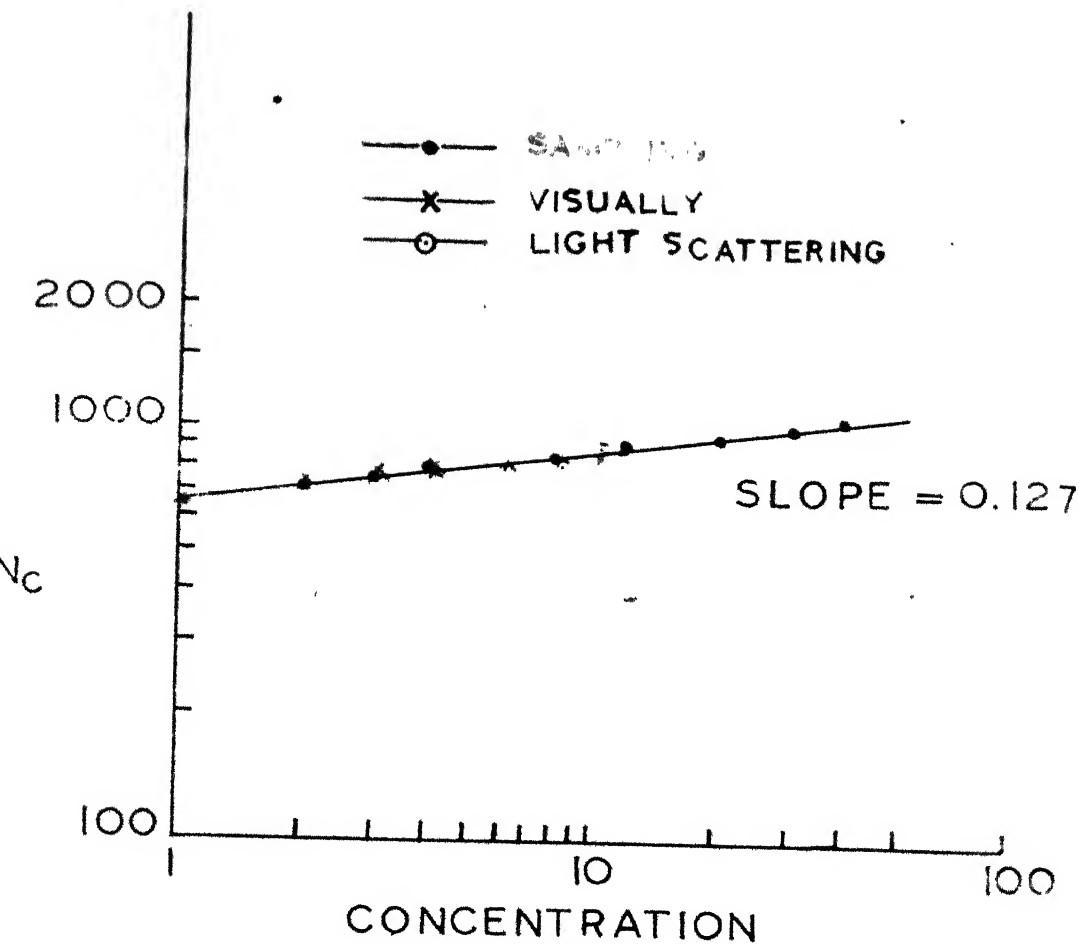
FIG. 3·2 – COMPARISON OF N_c-VALUES
OBSERVED BY THREE
DIFFERENT METHODS

In second set of runs, the whole processes were repeated to get N_c-values at different impeller heights from the tank of bottom. In this set propellers of diameter 6.0 cm, 8 cm and paddle impeller of 5.1 cm were used.

RESULTS AND DISCUSSION

4.1 Equivalence of N_c-values observed by the three methods:

To determine the N_c-values from sampling method, the local sample concentrations were plotted against different stirrer (marine propeller of diameter 6.0 cm) speeds, taking average tank solid loadings as a parameter (Fig.4.1,4.2 and4.3). The curves show a maxima. and the corresponding stirrer speed may be taken (discussed later) as the critical speed of suspension.

Similarly in visual observations, the criteria applied by Zwietering (1) for complete suspension was used and the N_c-values were found out. These N_c-values were also observed by light-scattering technique.

The data is tabulated in table (5). It is evident, that N_c-values from the three methods of observation for a specified system are identical. The differences are within 3%. It, thus, establishes the validity of visual observations of N_c, as employed by Zwietering. It may be noted that the determination of N_c by either sampling method or light-scattering technique is a time consuming and difficult process. It, has however been used in limited experiments of the present study to check if visual observations for N_c are correct.

4.2 A model for suspension and homogenisation:

A close scrutiny of figures4.1,4.2 and4.3 suggest a model of homogenisation process of particle concentrations, suspension being the first step. At any sampling point excluding the non-circulating
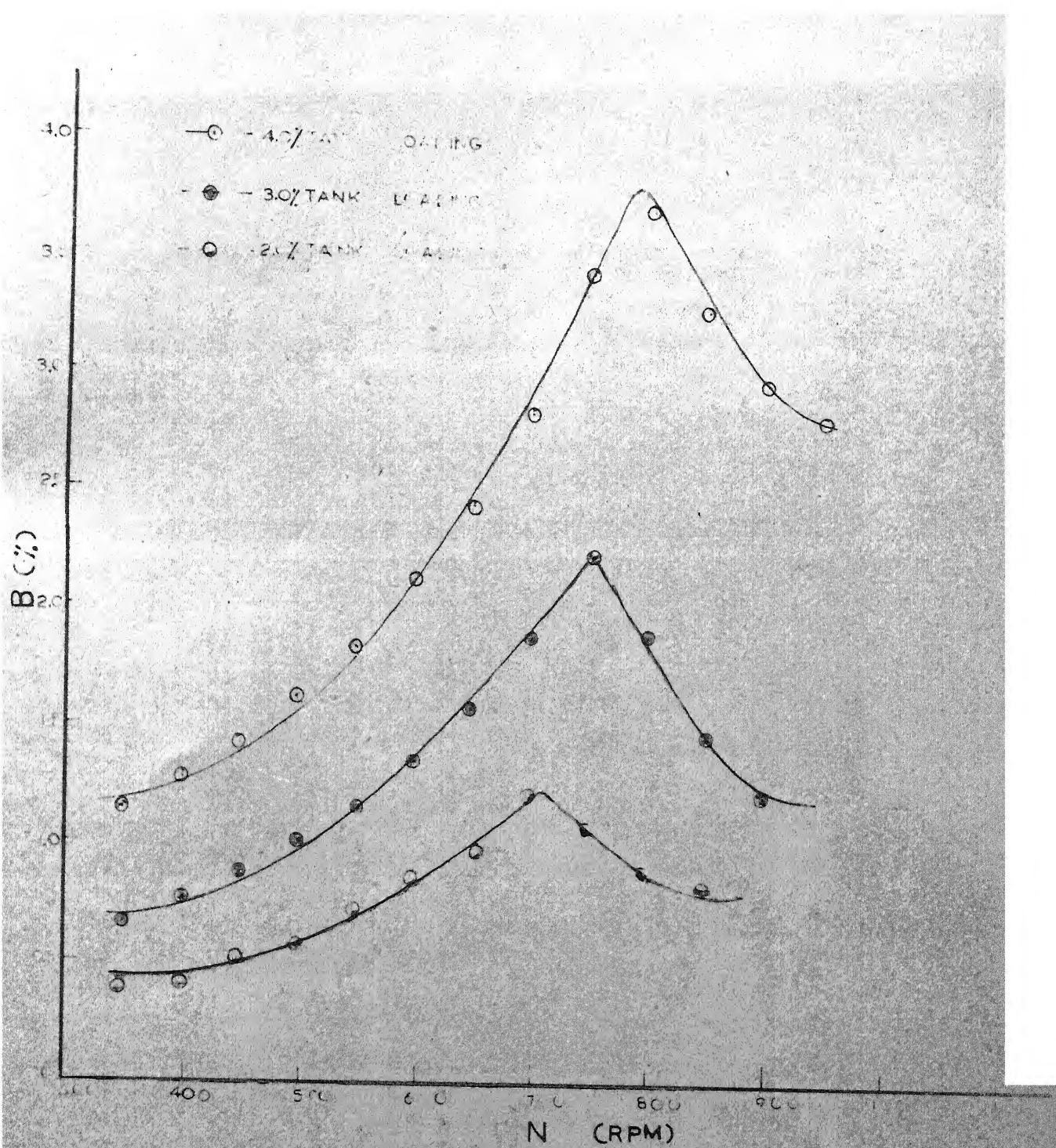
FIG. 4.I – EFFECT OF ROTATIONAL SPEED OF MIXER ON
LOCAL SAMPLE CONCENTRATION
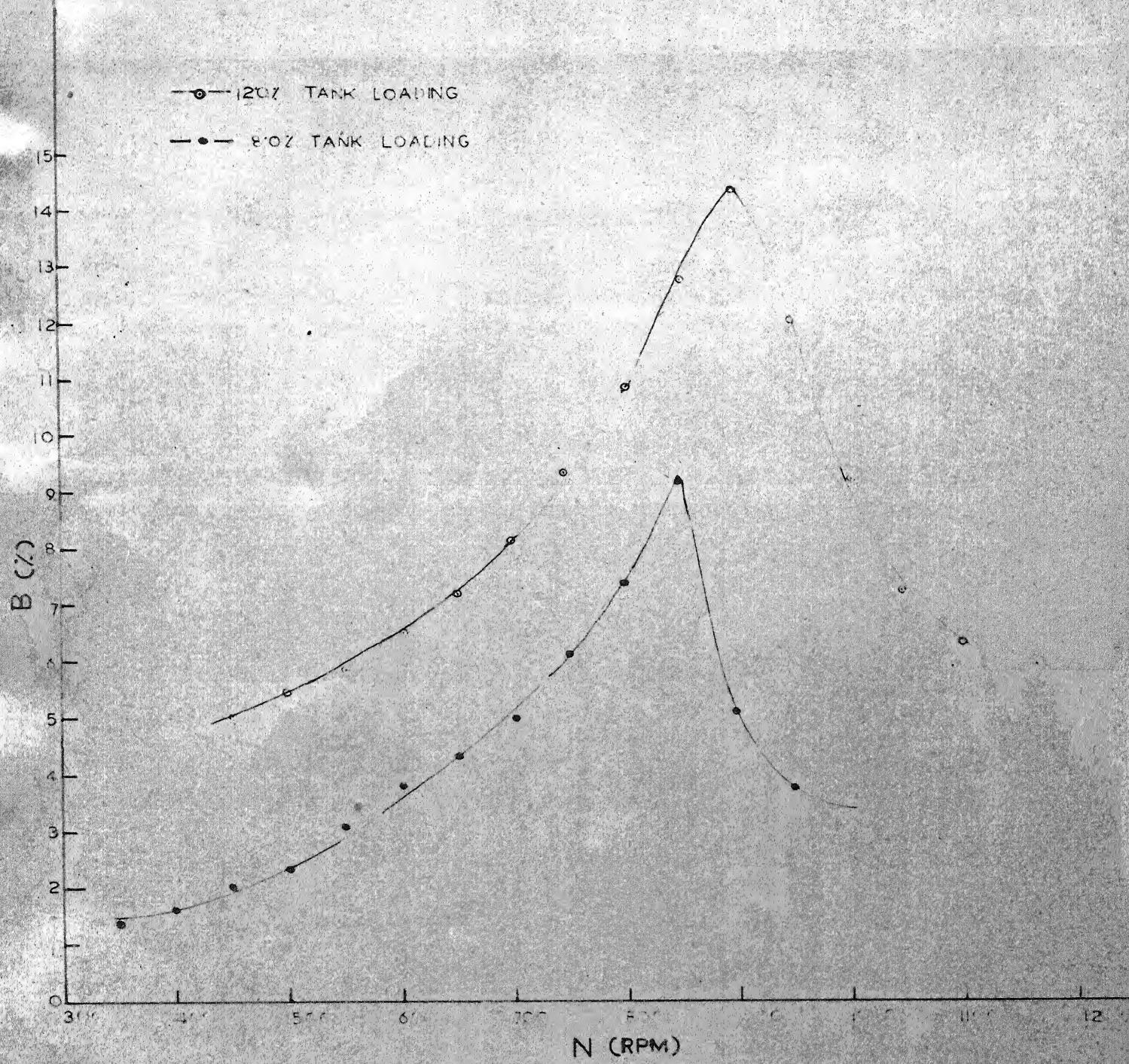
FIG 4.2 - EFFECT OF ROTATIONAL SPEED OF MIXER ON LOCAL SAMPLE CONCENTRATION
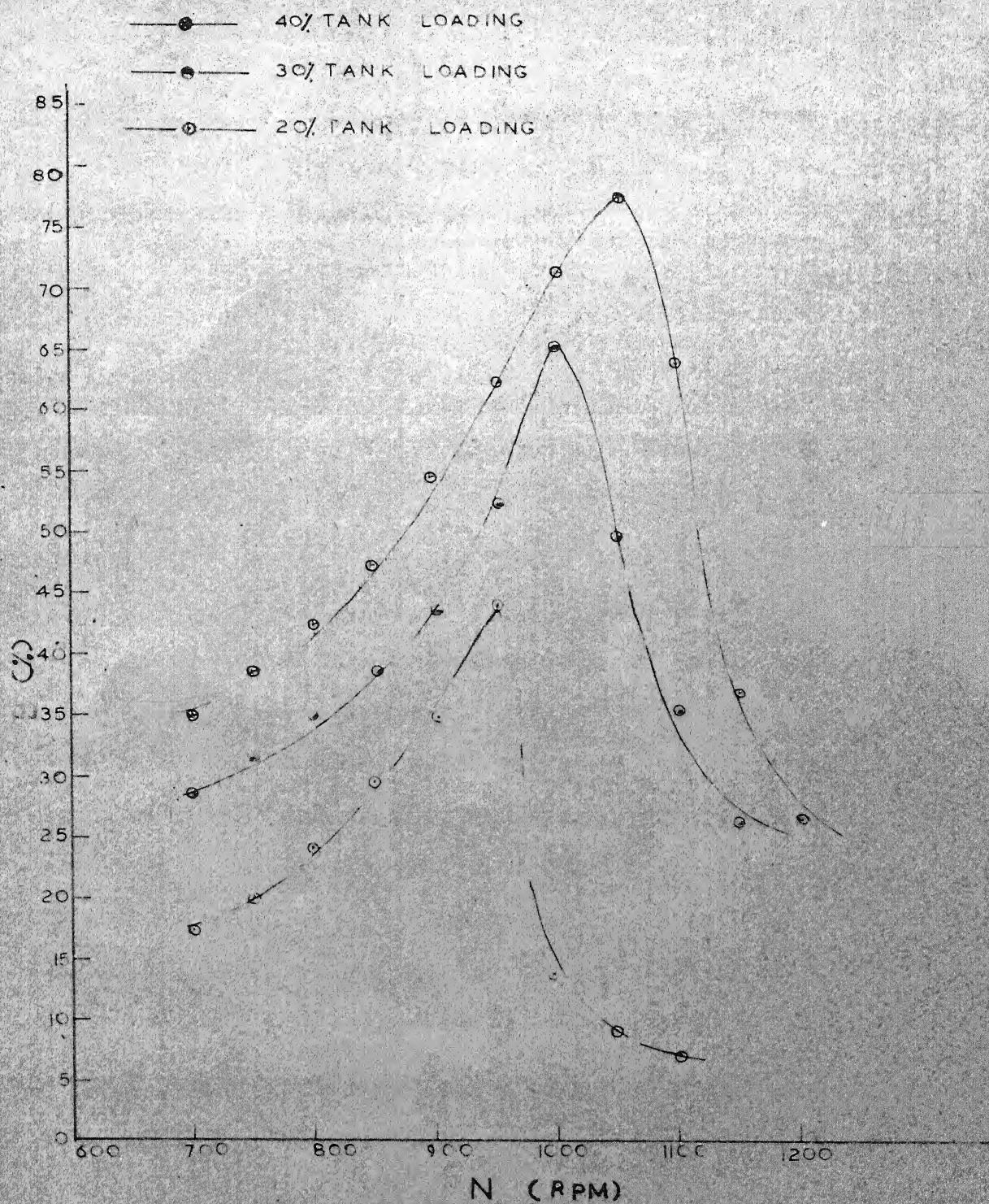
FIG. 4.3 - EFFECT OF ROTATIONAL SPEED OF MIXER
ON LOCAL SAMPLE CONCENTRATION

zones, which depend upon the type of flow pattern the stirrer generates, the local value of particle concentration increases with the increasing speed of stirrer due to progressive lift-up of particles from the base until a maxima is reached. This corresponds to the break-point and represents the critical speed N_c. At this point the suspension is complete and the suspension effects fade away with homogenisation effects start playing the dominant role, which cause the accumulated particles disperse to the depleted non-circulating zones. The implications of this model are illustrated in figure 4.4.

4.3 Effect of particle concentration on N_c:

A few typical plots of N_c versus particle concentrations are given in figure 4.5, 4.6 and 4.7. It can be observed that the relationship between N_c and particle concentrations expressed as B is linear on a log-log graph. Also, these lines are shifted in a parallel fashion depending on the magnitude of the parameter, tank diameter (T) for a given mixer, clearance from the tank bottom and number of baffles. In figure 4.8 the value of clearance from the tank bottom (T/C) was taken as T/9. The slope of all these lines is approximately 0.13. Therefore, the value of exponent of B in Zwietering's relation from the present findings should be 0.13 which is in excellent agreement with the Zwietering's exponent-value of 0.13 also, the value of this exponent is independent of the number of baffles,type of mixer and clearance from the tank base.

4.4 The value of γ and 't' in the Zwietering's relation:

From the data, plots between S' and T/D were drawn as shown in figure 4.9, for a given geometrical and physical system which includes two types of impellers used.
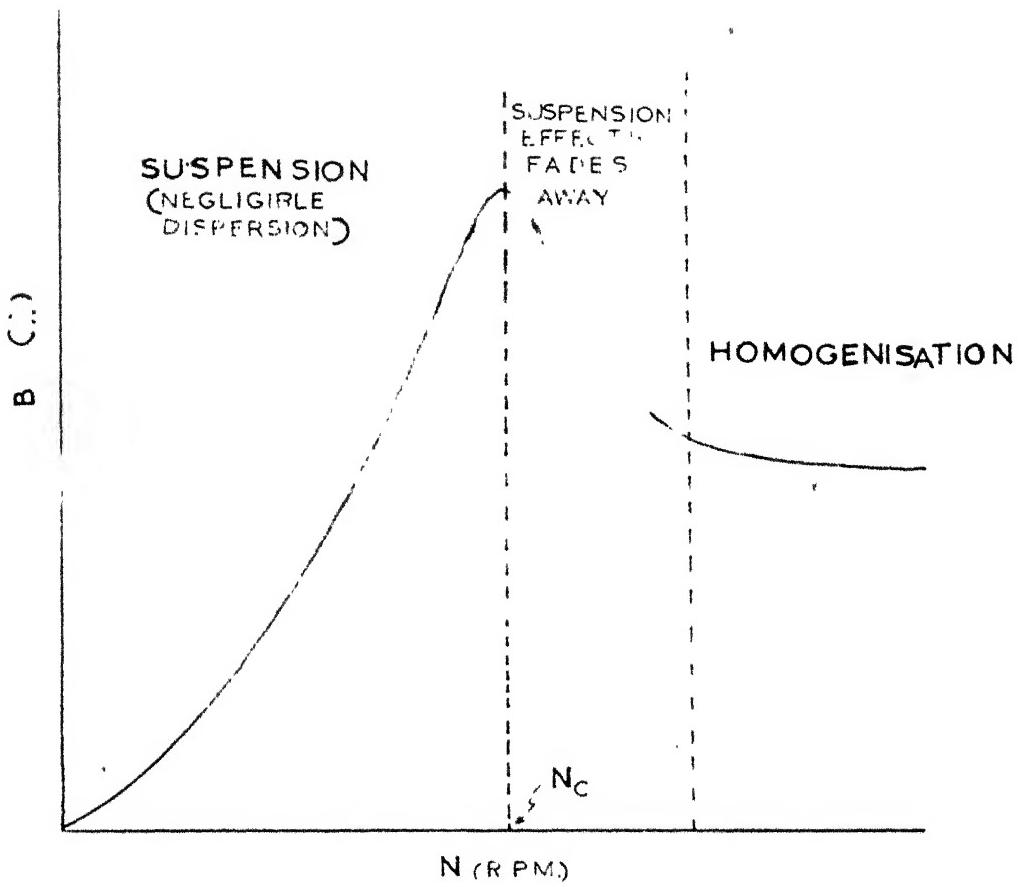
FIG. 4.4 MODEL OF SUSPENSION
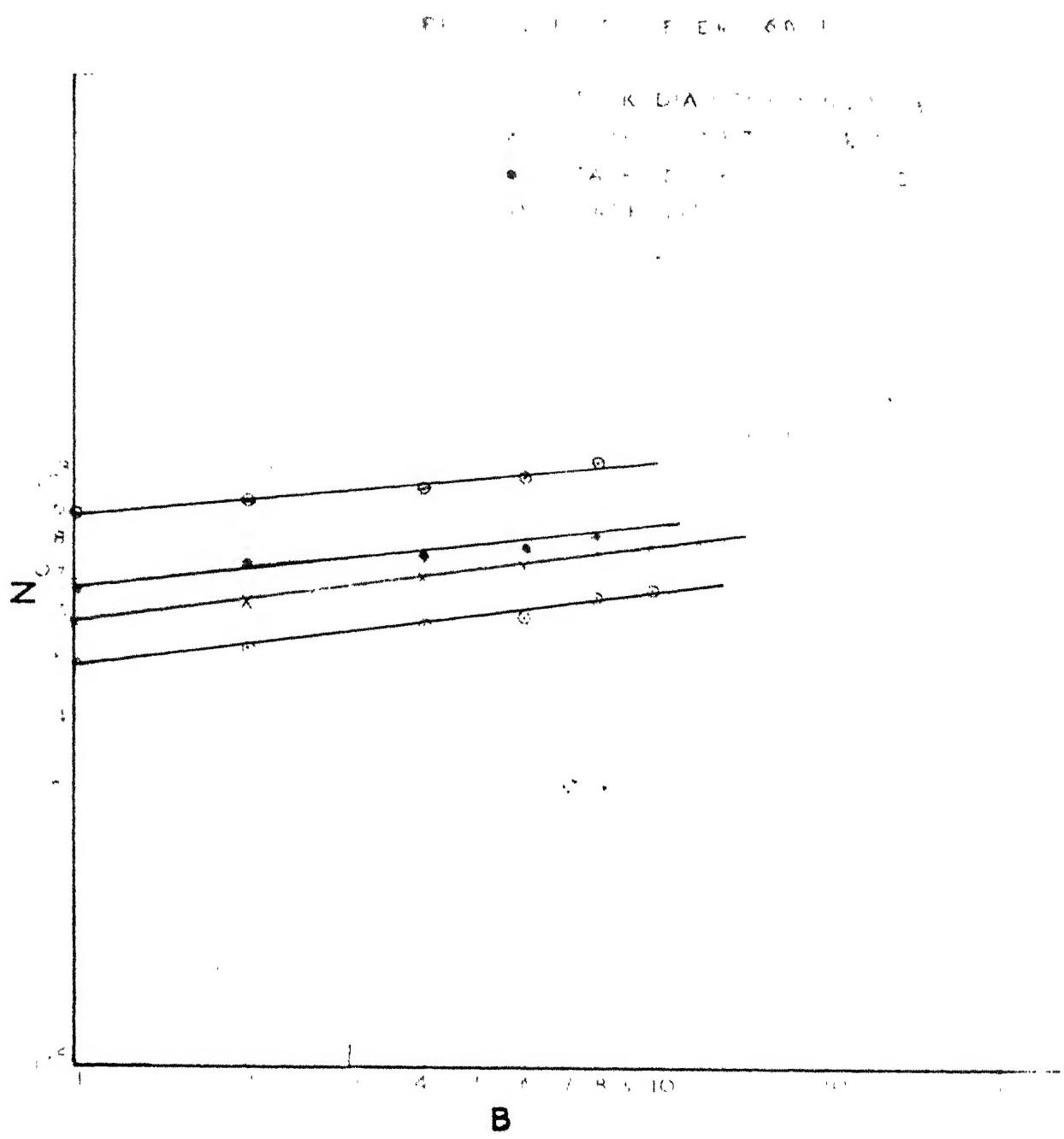
FIG – 4.5 EFFECT OF SOLID LOADINGS ON N
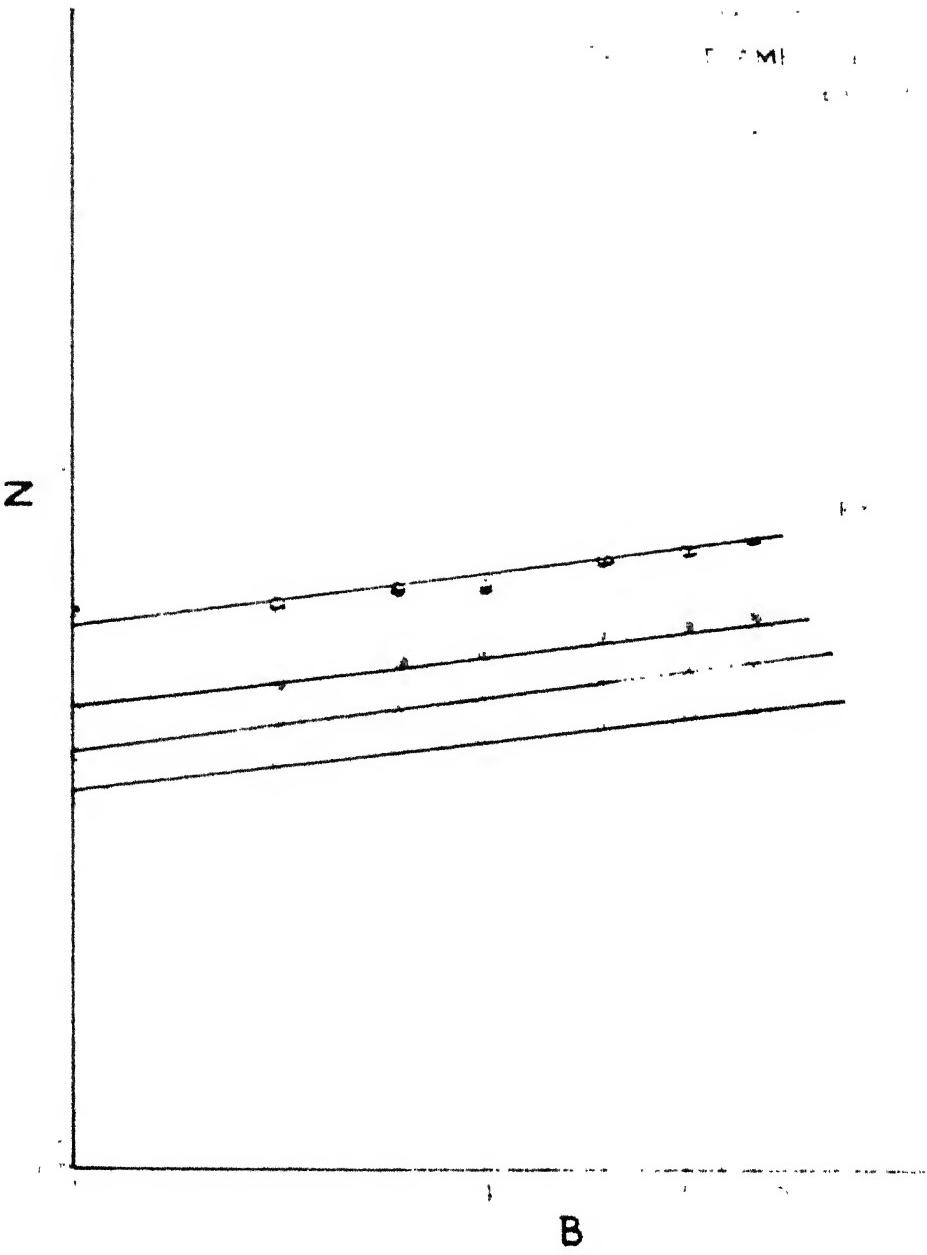
FIG.—4.6 EFFECT OF SOLID LOADING ON N
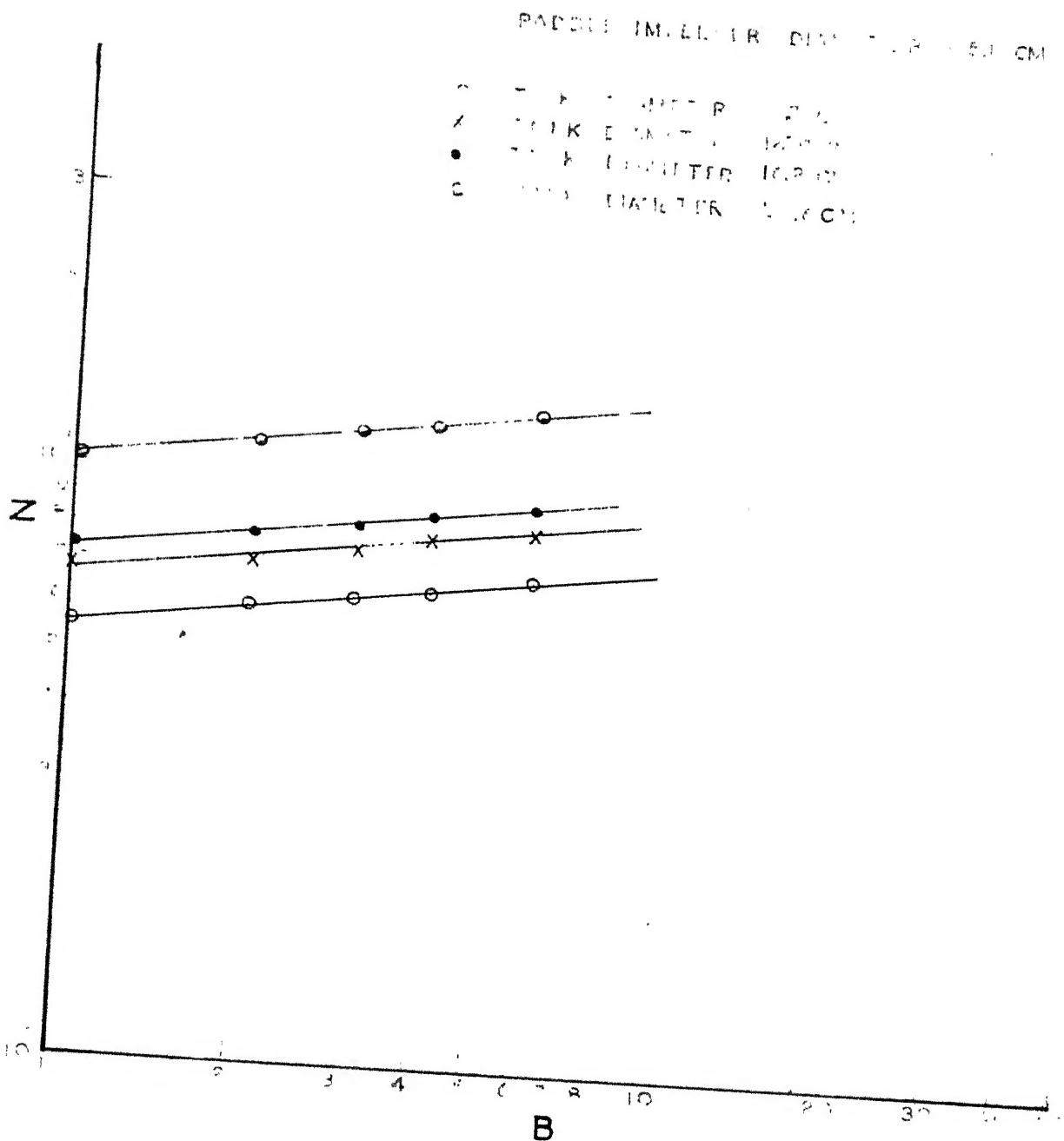
FIG.-4.7 EFFECT OF SOLID LOADING ON N
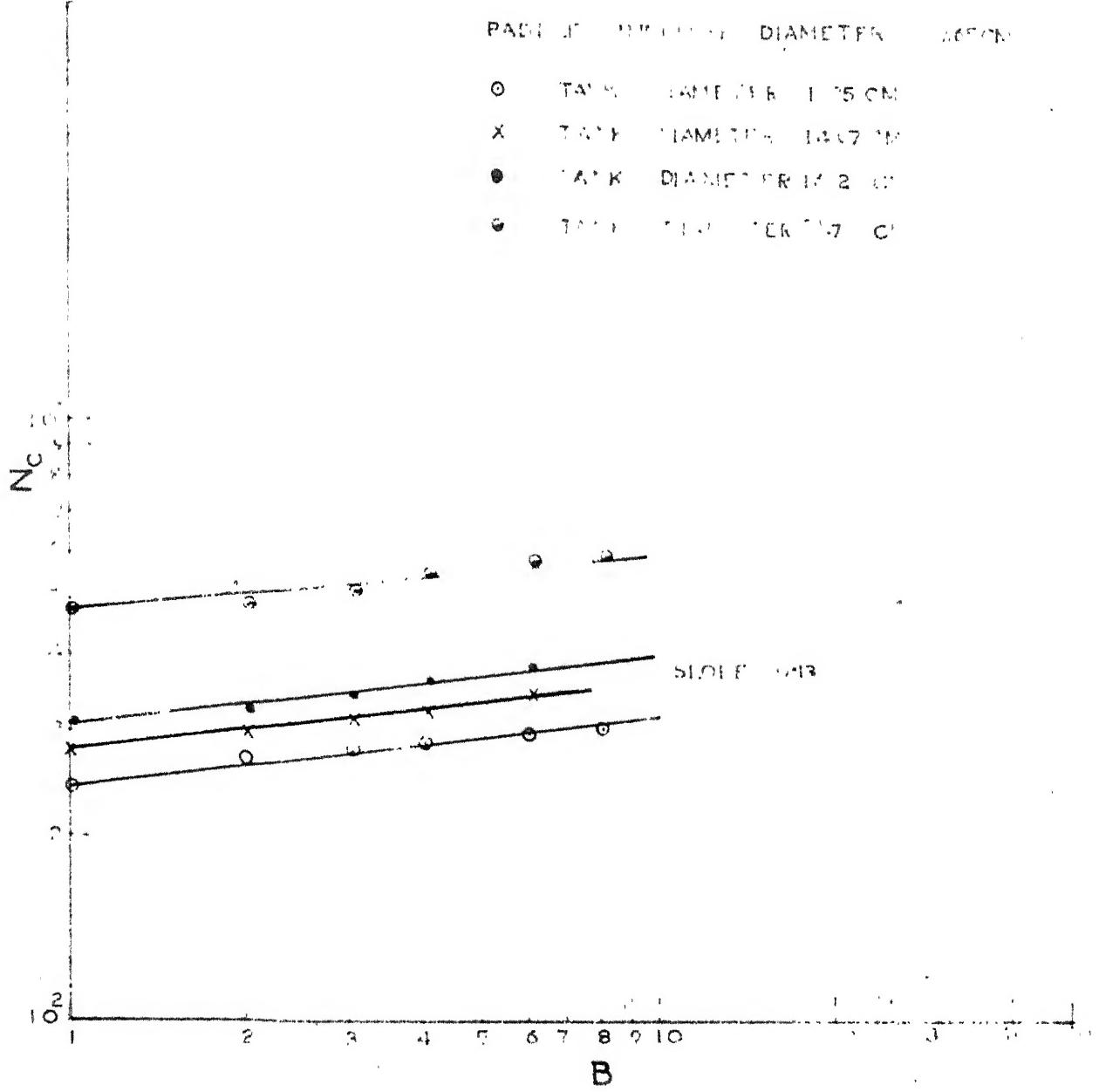
FIG. -4.8 DEPENDENCE OF N_c ON SOLID LOADINGS
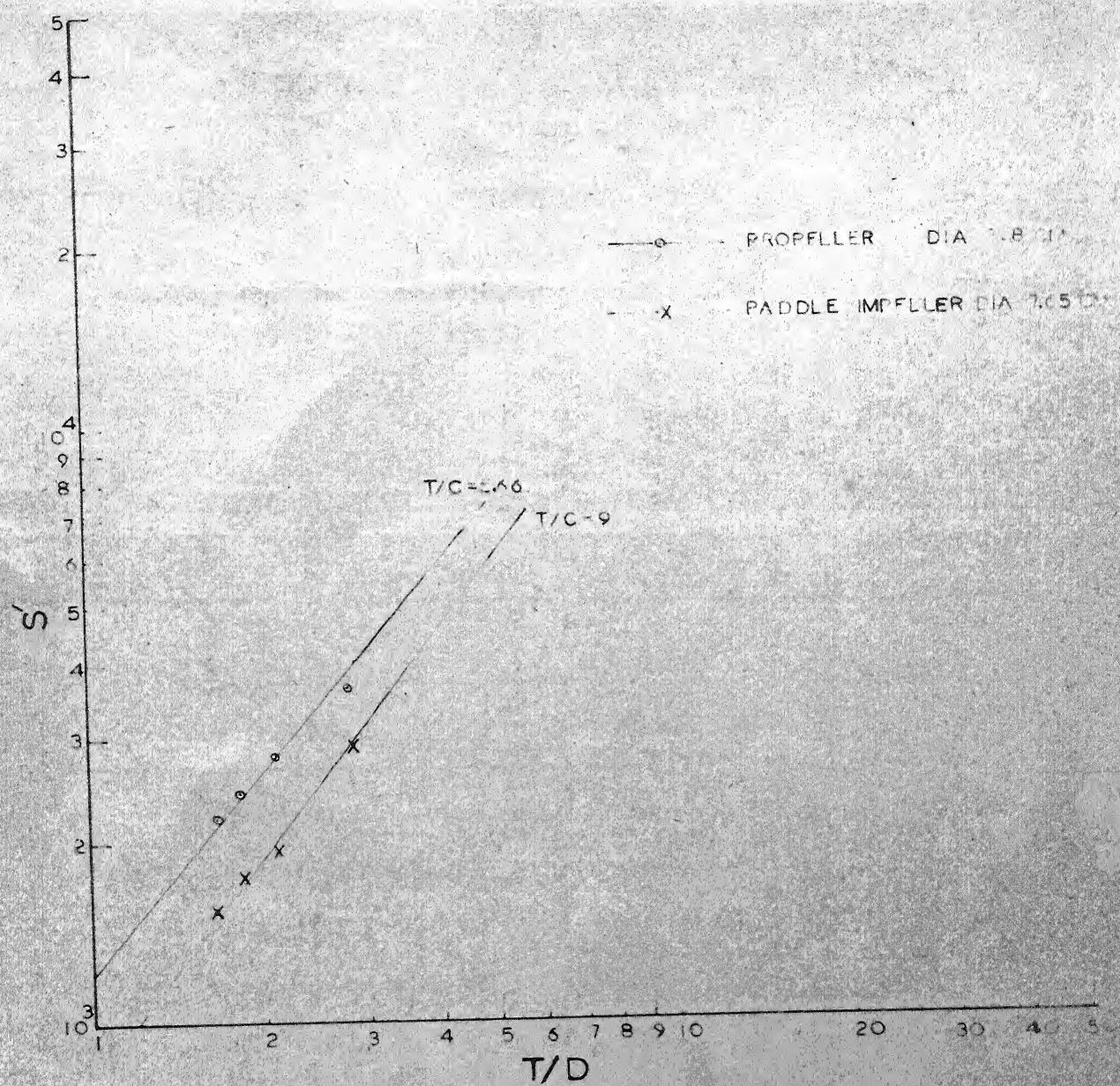
FIG 4.9 – DEPENDENCE OF Υ & t ON TYPES
OF IMPELLERS USED

Zwietering defined dimensionless quantity S in the following way:

$$S = \frac{N_c \, D^{0.85}}{\nu^{0.1} \, D_p^{0.2} \, (g \Delta \rho / \rho_\ell)^{0.45} \, B^{0.13}} \quad \cdots \cdots 4.1$$

or $\quad S = S' \, A$

where $A = 1/\nu^{0.1} \, D_p^{0.2} \, (g \Delta \rho / \rho_\ell)^{0.45} \, B^{0.13}$

$$S / A = \gamma (T/D)^t$$

Therefore from a log-log plot between S' and T/D, the values of γ and 't' can be determined. The values so obtained are given in the table 4.1.

TABLE 4.1

Mixer		T/C	γ	't'
Type	Dimension			
Marine propeller	6.0 cm – dia.	5.66	2	1.08
Marine propeller	7.8 cm – dia.	5.66	2	0.98
Flat blade paddle impeller	5.1 cm – dia.	9.00	1.27	1.29
Flat blade paddle impeller	6.4 cm – dia.	9.00	1.32	1.27
Flat blade paddle impeller	7.6 cm – dia.	9.00	1.20	1.20

From the table it is evident that γ depends on the type of mixer chosen to suspend the particles. It doesnot depend upon the clearance from the tank bottom, nor on the dimension of the mixer (Fig.4.10). Value of 't', however is observed to depend upon the

⊙   PROPELLER DIA.   6.O CM.
●   PROPELLER DIA.   7.8 CM.

10^4

$N D_c^{0.85}$

$T/C = 566$

10^3

T/D

10   12   15
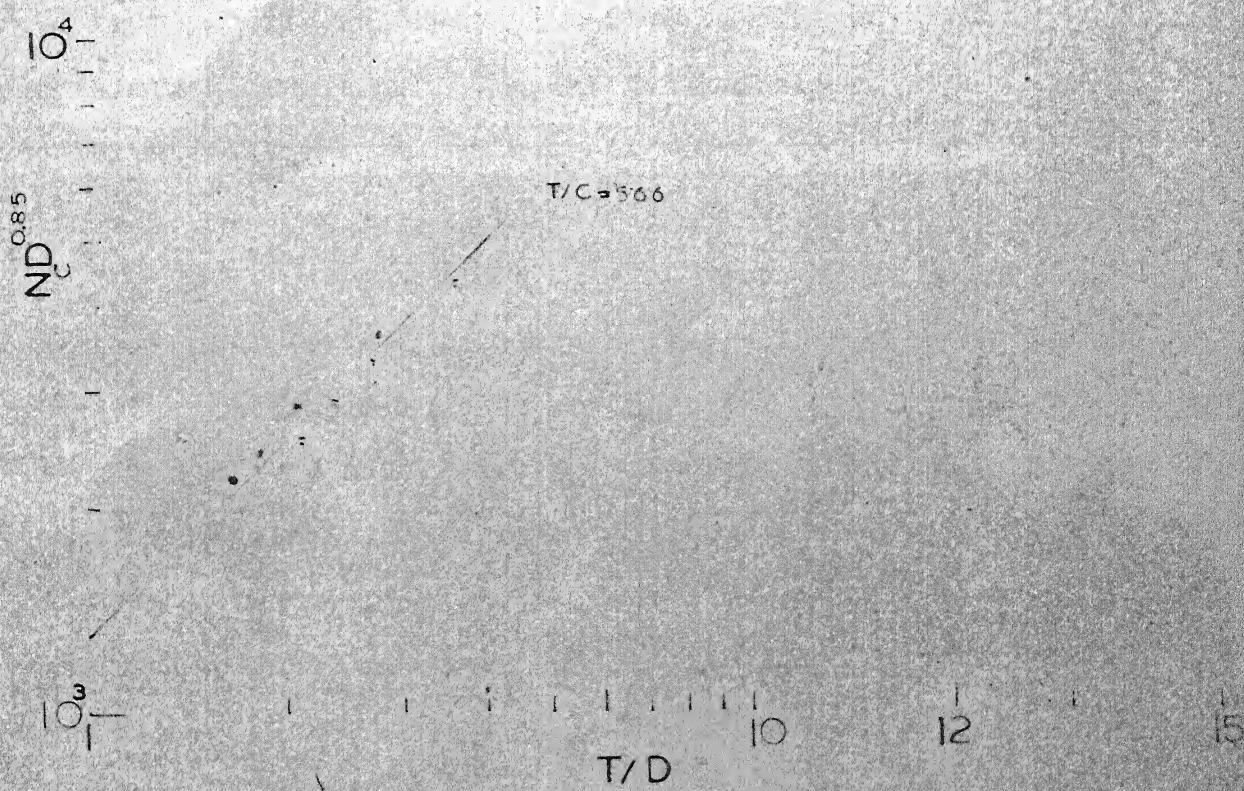
FIG. 4.IO — EFFECT OF PROPELLER DIAMETER
ON ψ

clearance from the tank bottom, since the slope of the lines in figures 4.11 and 4.12, changes with T/C. The figures 4.11 and 4.12 were drawn by getting relevant values from the plot of N_c-values versus T/C as shown in figures 4.13 and 4.14. The value of 't' also depends upon the type of mixer.

Figure 4.15 shows a log-log plot of 't' versus T/C. The relevant values are obtained by cross reading from the plot of $N_c D^{0.85}$ versus T/D as shown in figure 4.11 and 4.12. It can be observed from the figure that 't' varies as part of $(T/C)^{-0.12}$ for paddle mixer and $(T/C)^{-0.40}$ part for propeller. The corresponding relations to evaluate 't' comes to,

$$t = k_1 \, (T/C)^{-0.4} \quad \text{for square pitch propeller}$$
$$t = k_2 \, (T/C)^{-0.12} \quad \text{for paddle mixer}$$

where the values of k_1 and k_2 are respectively. It can also be observed from the figure that below the value of T/C equal to 5.0, 't' for both the mixers is approximately the same. This in other words means that the suspension characteristics of both type of mixers (square pitch mrine propeller and six flate blade paddle impeller) are more or less similar for T/C less than 3.0.

FIG 4.11 DEPENDENCE OF ψ & t ON T/C FOR PROPELLER
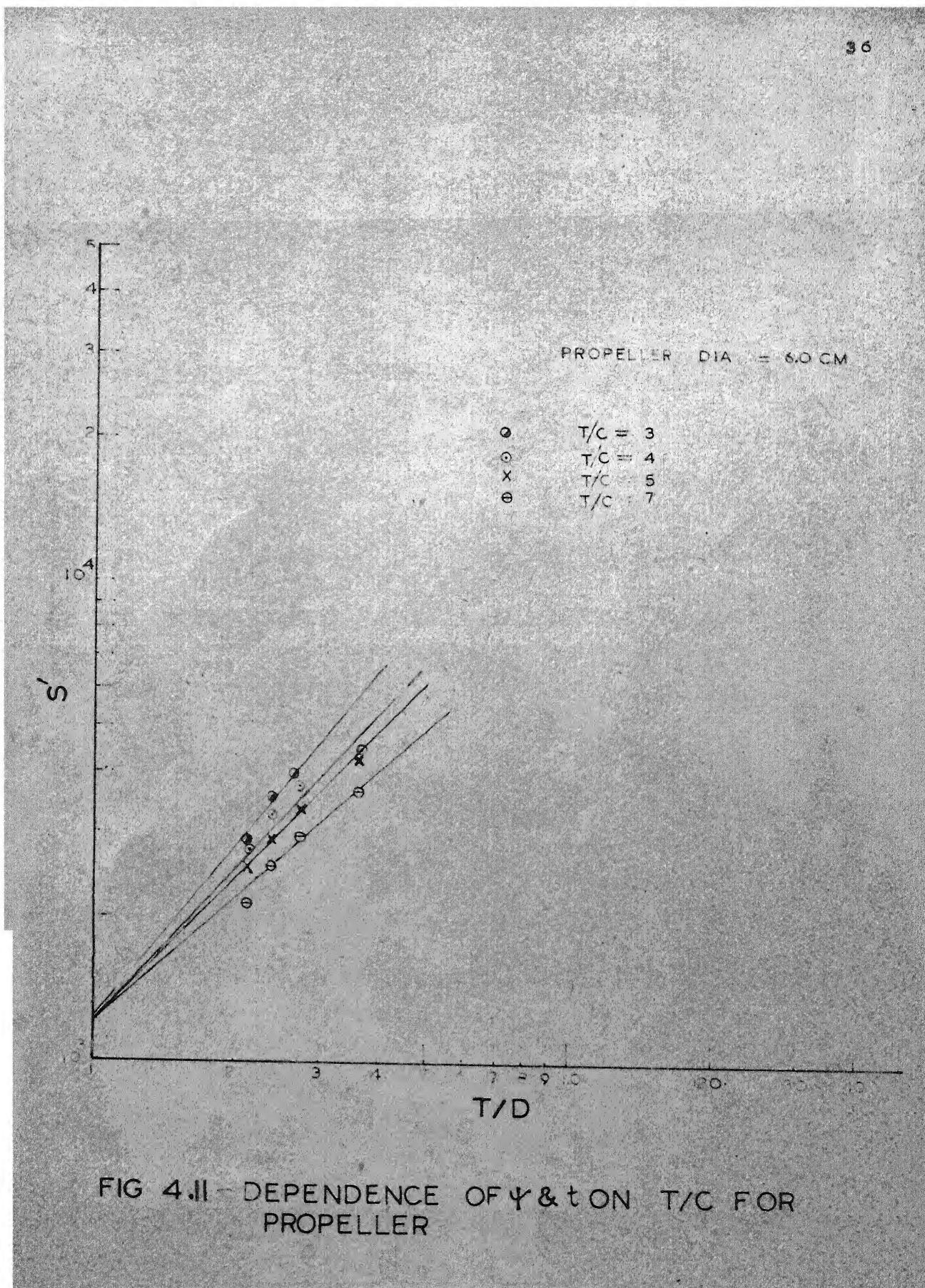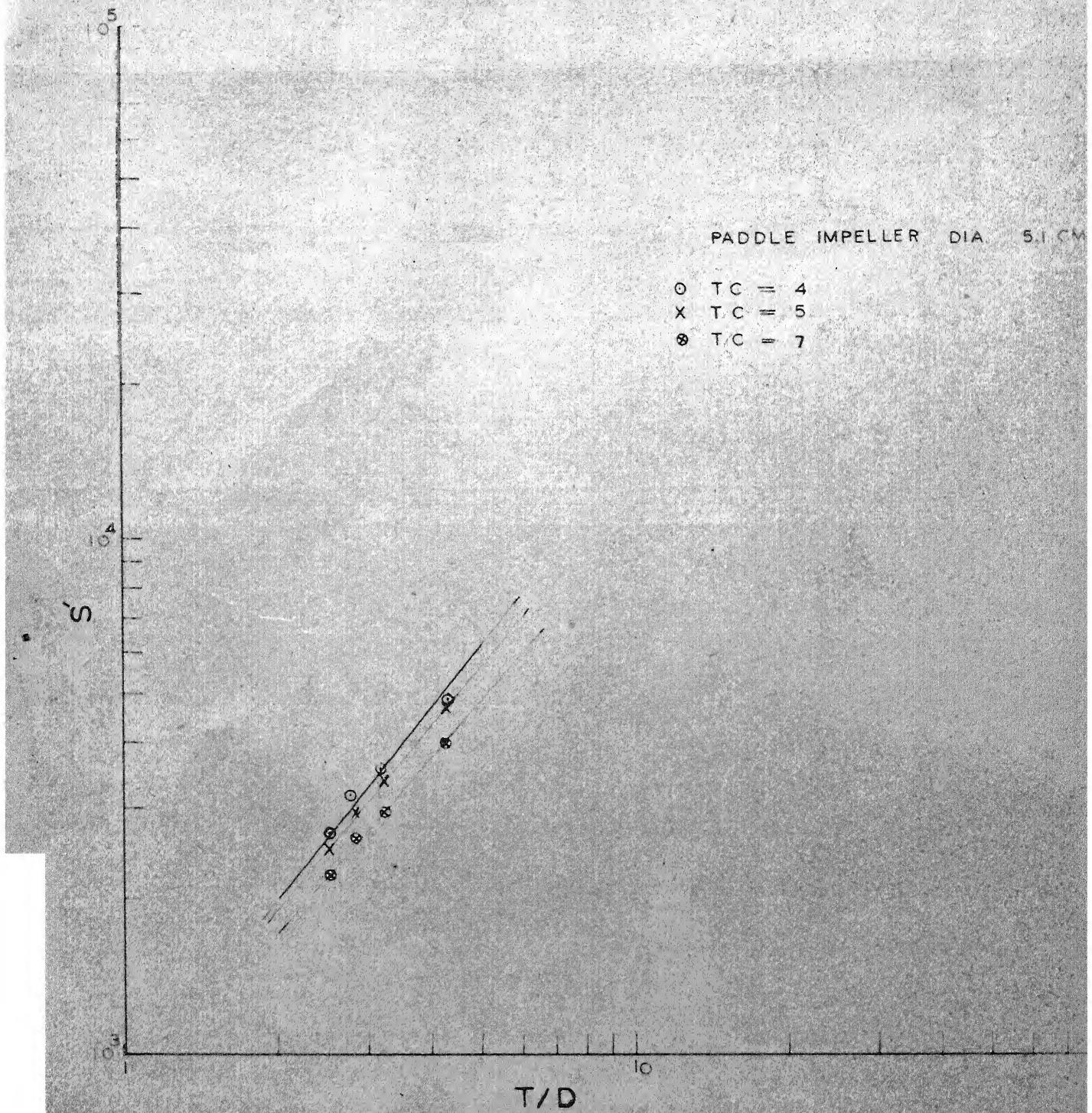
FIG. 4.12 – DEPENDENCE OF Y & t ON T/C FOR PADDLE IMPELLER
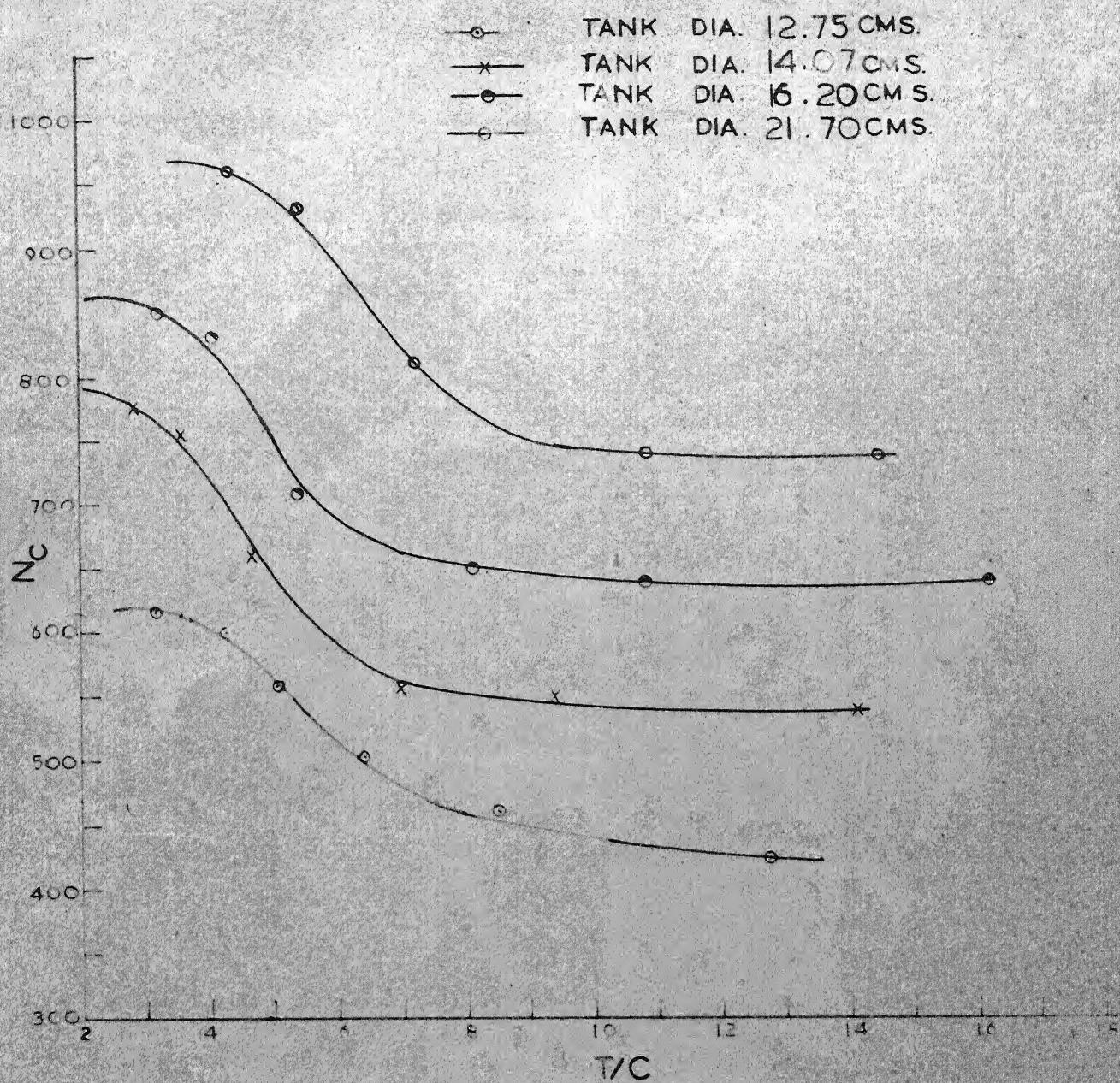
FIG. 4.13—EFFECT OF CLEARANCE ON N_c — VALUES
FOR PROPELLER DIAMETER = 6.0 CM
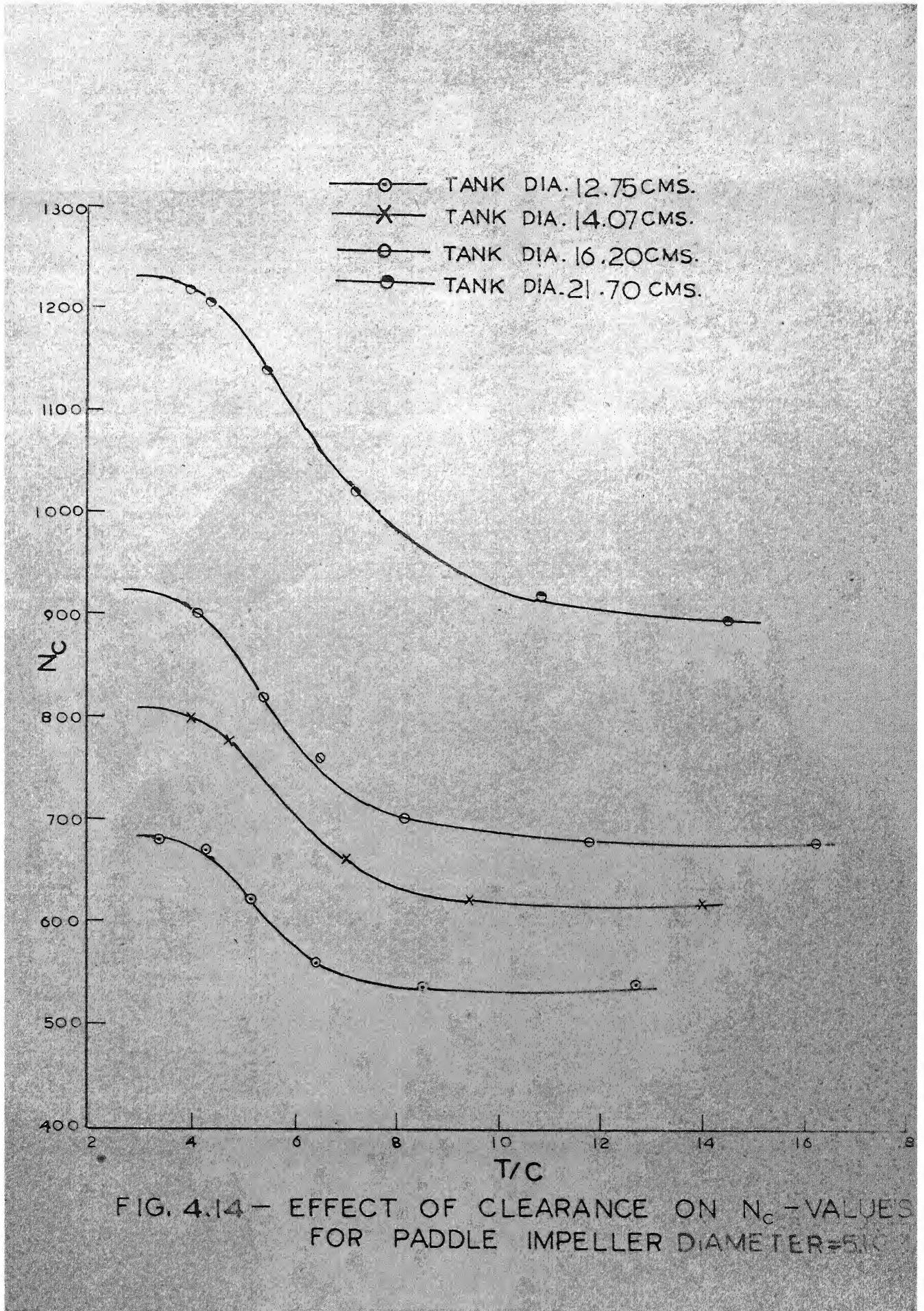
FIG. 4.14 — EFFECT OF CLEARANCE ON N_C —VALUES
FOR PADDLE IMPELLER DIAMETER = 5.10
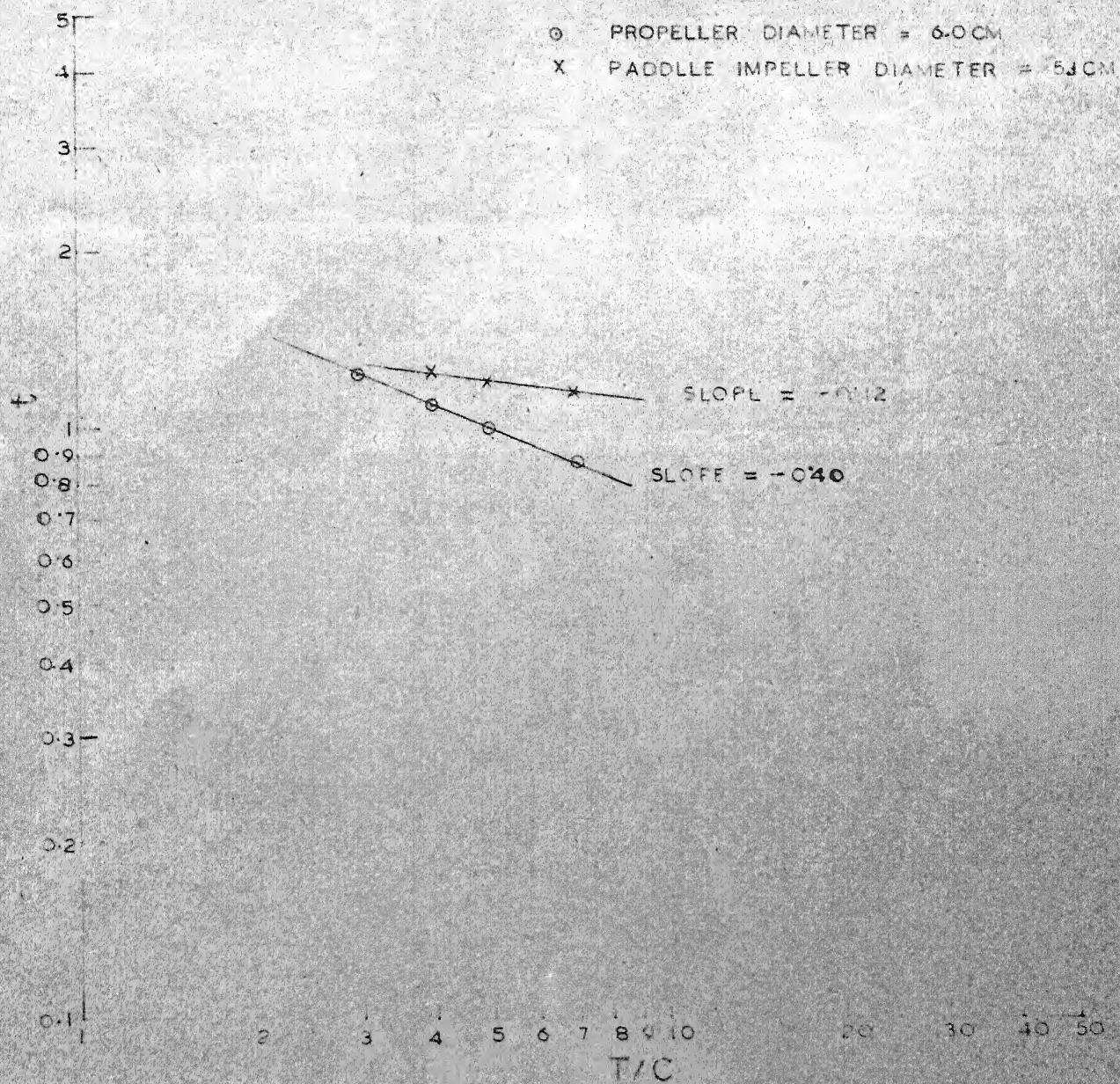
FIG. - 4.15 DEPENDENCE OF 't' ON T/C FOR PROPELLER AND PADDLE IMPELLER

4.5 Dependence of mixer diameter on N_c:

From the particle concentration versus N_c plots, N_c-values vere found out for a constant clearance, tank diameter and particle concentration. These values were then plotted against the diameter of the impellers. Figure 4.13 shows such a plot for a paddle-mixer. Since, only two sizes were available such a plot could not be completed for marine propeller. The slope of the curve comes to 2.14, i.e.

$$N_c \text{ varies as } 1/D^{2.14}$$

Now from Zwietering's relation,

$$N_c \text{ varies as } (T/D)^a \ 1/D^b$$

From present experiments, the value of 'a' is 1.3. Therefore,

$$b = 2.14 - 1.3$$
$$. = 0.84$$

Which is in excellent agreement with the value of 0.85, quoted by Zwietering.
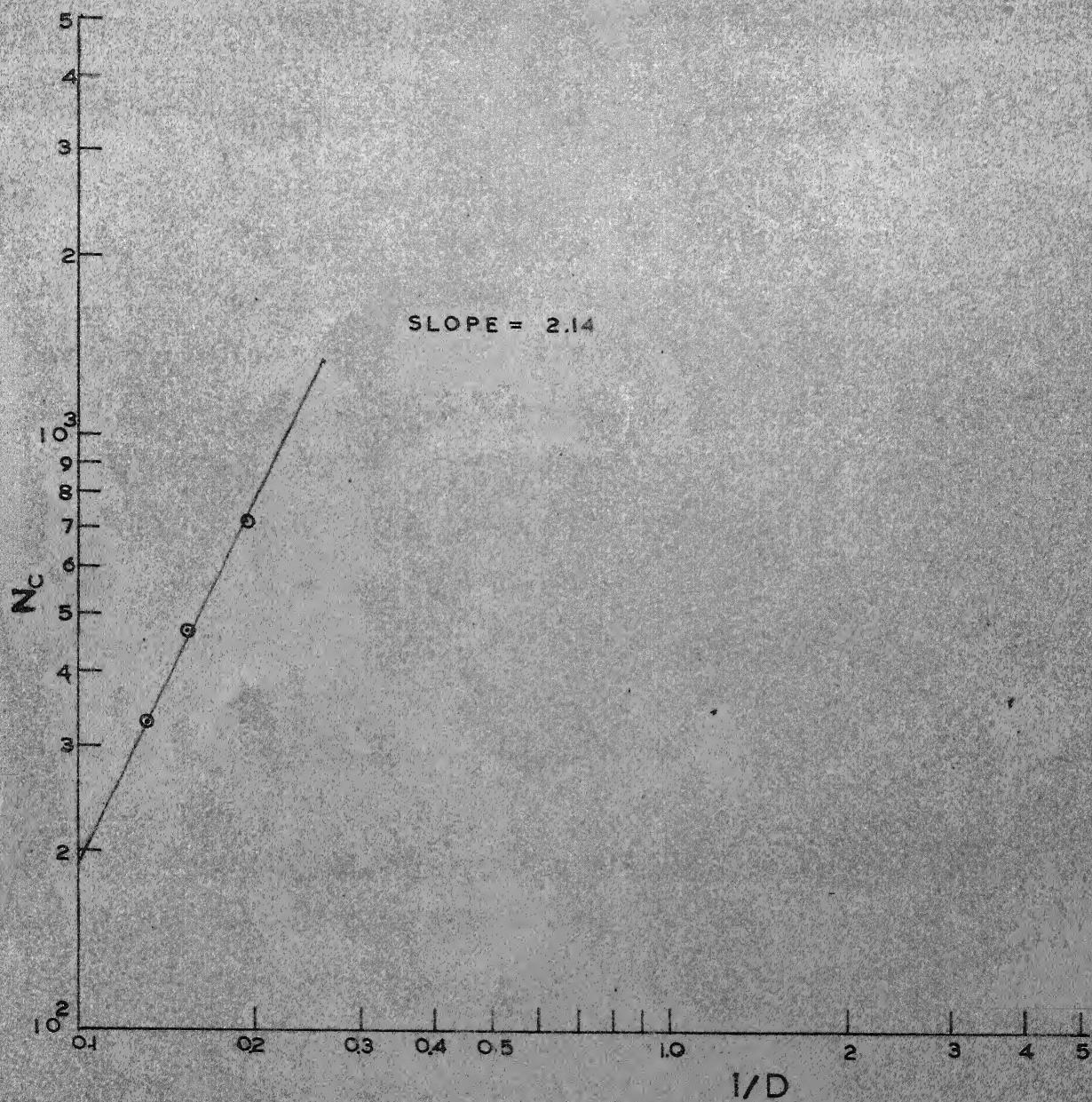
FIG.-4.16 DEPENDENCE OF MIXER DIAMETER
ON N_c

CHAPTER - 5

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the present study:

(i) The critical speed of suspension, N_c, observed from three different methods i.e.

      (a) by physically withdrawing the local samples of particulate suspensions.

      (b) through light-scattering technique and

      (c) by visual observations

are more or less same. Therefore, it can be concluded that N_c based on visual observations can be taken as the true N_c-values although the method appears to be subjective.

(ii) A model of suspension is proposed on the basis of experimental data obtained by physically withdrawing the local samples. Accordingly to this model, the solids are suspended first completely at a specified r.p.m. of the impeller and subsequently they are distributed throughout the tank region in response to a homogenisation step.

(iii) The Zwieterings relation for calculating the value of N_c in a stirred tank with particulate suspensions is validated because of the correctness of N_c-values observed visually. Also,

      (a) N_c varies as $B^{0.13}$ as reported by Zwietering.

      (b) N_c varies as $1/D^{0.84}$ which is also as contained in Zwietering relation.

(iv) γ contained in the Zwietering relation is a function of the type of stirrer, and not on its dimension or clearance from the tank bottom.

(v) 't', the exponent of (T/D) in the relation is a function of the type of the stirrer and its clearance from the tank bottom. There exists a relationship for 't' versus the clearance expressed in dimensionless form according to,

(a) $t = k_1 \, (T/C)^{-0.4}$ for square pitch propeller and

(b) $t = k_2 \, (T/C)^{-0.12}$ for paddle impeller.

Recommendations

It is recommended that similar work be continued with other types of impellers to throw more light particularly on the nature of γ and 't'.

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APPENDIX I

PHYSICAL PROPERTIES OF SOLID

1. Solid particles used   -   Spherical Glass Beads

    (i) Density of Solid Particles - 2.64 gm/cm^3

    (ii) Size of the Solid Particles - 500 micron

PHYSICAL PROPERTIES OF LIQUID

2. Liquid used   -   Distilled Water

    (i) Density of Distill Water - 1.00 gm/cm^3

    (ii) Viscosity of Distill Water - 0.9820 c.p.

APPENDIX I

DATA OBTAINED BY SAMPLING METHOD

$$T/H \ = \ 1.5$$
$$T/C \ = \ 5.66$$

No. of Baffles = 3
Width of Baffles = 0.1 T

TABLE – 1

Average local sample concentration at various (propeller) speeds, for different solid loadings.

P = 16.2 cm   D = 6.0 cm

N.	r.p.m.	Average Tank Concentration							
		2.0	3.0	4.0	6.0	12.0	20.0	30.0	40.0
1	350	0.410	0.675	1.125	1.400	–	–	–	–
2	400	0.425	0.775	1.275	1.600	–	–	–	–
3	450	0.500	0.800	1.425	1.950	5.00	–	–	–
4	500	0.575	1.025	1.600	2.500	5.50	–	–	–
5	550	0.760	1.160	1.835	2.290	5.90	–	–	–
6	600	0.840	1.575	2.000	3.500	6.50	–	–	–
7	650	1.000	1.500	2.500	4.360	7.25	–	–	–
8	700	1.250	1.800	2.900	5.400	8.30	17.50	28.50	35.00
9	750	1.100	2.300	3.475	6.150	9.35	19.5	32.20	38.55
10	800	0.900	1.800	3.700	4.300	10.80	24.50	35.30	42.00
11	850	0.800	1.470	3.330	9.450	12.80	29.00	38.00	47.00
12	900	–	1.230	3.200	5.000	14.00	36.00	44.00	54.50
13	950	–	–	2.800	3.700	12.10	44.00	53.50	62.50
14	1000	–	–	–	–	9.20	14.00	65.00	72.50
15	1050	–	–	–	–	7.00	9.00	50.50	78.20
16	1100	–	–	–	–	6.30	8.50	36.00	65.00
17	1150	–	–	–	–	–	–	25.50	37.00
18	1200	–	–	–	–	–	–	–	27.00

TABLE - 2

N_c-values determined by sampling technique

S.N.	Average Tank Concentration	N_c(r.p.m.)
1	2.0	710
2	3.0	750
3	4.0	780
4	8.0	850
5	12.0	900
6	20.0	950
7	30.0	1000
8	40.0	1050

TABLE - 3

N_c- values observed visually for propellers

$$T/H = 1.5$$
$$T/C = 5.66$$
$$No. \ of \ Baffles = 3$$
$$Width \ of \ Baffles = 0.1 \ T$$

Run 1

$$D = 6.0 \ cm$$

S.N.	Concentration %	N_c (r.p.m.)			
		T = 12.75 cm	T = 14.07 cm	T = 16.2 cm	T = 21.7 cm
1	1.0	–	–	660	880
2	2.0	520	620	730	930
3	3.0	–	–	750	–
4	4.0	570	690	780	980
5	6.0	590	720	820	1030
6	8.0	635	760	–	1090
7	10.0	660	780	–	–
8	12.0	–	800	–	–

coutd.

T/D	N_c
2.125	520
2.350	630
2.700	700
3.600	920

Run 2   D = 7.8   cm

S.N.	Concentration %	N_c (r.p.m.)			
		T=12.75 cm	T=14.07 cm	T=16.2 cm	T=21.7 cm
1	1.0	—	—	—	—
2	2.0	460	520	650	750
3	3.0	—	—	—	—
4	4.0	510	570	680	820
5	6.0	540	600	700	850
6	8.0	560	630	720	900
7	10.0	580	650	750	920

T/D	N_c
1.600	460
1.760	520
2.125	620
2.700	750

TABLE-4

N_c-values observed by light scattering technique
for propellers

T/H	=	1.5
T/C	=	5.66
No. of Baffles	=	3
Width of Baffles	=	0.1 T

Run 1   D = 6.0 cm

S.N.	Concentration %	N_c (r.p.m.)			
		T = 12.75 cm	T = 14.07 cm	T = 16.2 cm	T = 21.7 cm
1	1.0	460	560	640	850
2	2.0	500	610	700	920
3	3.0	—	—	760	950
4	4.0	560	690	780	970
5	6.0	580	710 ·	810	1020
6	8.0	630	750	—	1070
7	10.0	650	770	—	—
8	12.0	—	800	—	—

T/D	N_c
2.125	510
2.350	620
2.700	680
3.620	900

Run 2   D = 7.8 cm

S.No.	Particle Concentration %	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.0 cm	T= 16.2 cm	T= 21.7 cm
1	1.0	380	410	480	650
2	2.0	420	440	520	700
3	3.0	440	480	550	740
4	4.0	460	510	570	760
5	6.0	480	540	590	780
6	8.0	500	550	620	800
7	10.0	510	560	640	810

T/D	N_c
1.63	420
1.80	440
2.08	520
2.78	700

TABLE-5   Comparision of N_c-values observed by three different methods.

Tank diameter   = 16.2 cms

Propeller diameter = 6.0 cms

T/H   = 1.5

T/C   = 5.66

No. of baffles = 3

Width of Baffles = 0.1T

S.N.	Particle-Concentration %	N_c (r.p.m.)		
		Sampling Method	Visually	Light Scattering Method
1	1.0	–	660	640
2	2.0	710	730	700
3	3.0	750	750	760
4	4.0	780	780	780
5	6.0	–	820	810
6	8.0	850	840	840
7	10.0	–	860	850
8	12.0	900	900	880
9	20.0	950	–	–
10	30.0	1000	–	–
11	40.0	1050	–	–

TABLE-6

N$_c$-values observed visually for propellers and
paddle impeller.

T/H	= 1.5
T/C	= 5.66
No. of Baffles	= 4
Width of Baffles	= 0.1T

Run1 Propeller diameter = 6.0 cm

S.N.	Particle-Concentration %	N$_c$ (r.p.m.)			
		T = 12.75 cm	T = 14.07 cm	T = 16.2 cm	T =21.7 cm
1	1.0	480	560	650	850
2	2.0	510	610	710	910
3	3.0	540	640	750	950
4	4.0	560	660	780	990
5	6.0	580	700	820	1060
6	8.0	·620	730	850	1090
7	10.0	630	740	870	1130

T/D	N$_c$
2.125	520
2.35	630
2.70	720
3.60	930

Run 2　　　　　　　Propeller diameter = 7.8 cm

S.No.	Particle-Concentration %	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.07 cm	T= 16.2 cm	T=21.7 cm
1	1.0	350	410	480	650
2	2.0	400	450	520	680
3	3.0	420	480	550	720
4	4.0	430	500	570	750
5	6.0	450	520	600	780
6	8.0	470	540	630	810
7	10.0	480	550	650	850

T/D	N_c
1.63	390
1.80	430
2.08	500
2.78	640

Run 3　　　　　　　Paddle Impeller diameter = 5.1 cm

S.No.	Particle-Concentration %	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.07 cm	T= 16.2 cm	T= 21.7 cm
1	1.0	570	660	740	1050
2	2.0	590	720	800	1140
3	3.0	620	760	840	1200
4	4.0	640	800	880	1250
5	8.0	–	–	–	–

T/D	N_c
2.50	590
2.76	720
3.18	800
4.26	1150

TABLE 7

N_c-values observed by light-scattering technique for paddle impeller.(diameter = 5.1 cm)

T/H = 1.5

T/C = 5.66

No. of Baffles = 4

Width of Baffles = 0.1T

S.No.	Particle-Concentration %	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.07 cm	T=15.2 cm	T=21.7 cm
1	1.0	570	650	740	1050
2	2.0	580	720	800	1140
3	3.0	610	750	840	1210
4	4.0	640	780	870	1240
5	6.0	670	820	930	1320
6	8.0	680	840	950	-

N̄c values observed by light-scattering technique for propellers

$$T/H = 1.5$$
$$T/Q = 5.66$$
No. of Baffles = 4
Width of Baffles = 0.1 T

Run 1   Propeller diameter 6.0 cm

S.No.	Particle concentration %	N_c (r.p.m.)			
		T=12.75 cm	T=14.07 cm	T=16.2 cm	T=21.7 cm
1.	1.0	480	540	650	840
2.	2.0	510	600	700	900
3.	3.0	540	630	730	950
4.	4.0	550	650	760	1000
5.	6.0	570	680	800	1050
6.	8.0	620	720	840	1080

Run 2   Propeller diameter 7.8 cm

S.No.	Particle concentration %	T=12.75 cm	T=14.07 cm	T=16.2 cm	T=21.7 cm
1.	1.0	360	400	480	660
2.	2.0	400	440	500	680
3.	3.0	420	480	540	720
4.	4.0	440	500	600	760
5.	6.0	450	550	600	760
6.	8.0	470	550	650	800

TABLE-8

N_c-values observed visually for flat bladed paddle impellers.

T/H   = 1.5

T/C   = 9.0

No. of Baffles   = 4

Width of Baffles = 0.1T

Run 1   D   = 5.1 cm

S.No.	Particle-Concentration %	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.07 cm	T= 16.2 cm	T= 21.7 cm
1	1.0	480	580	630	900
2	2.0	530	620	670	950
3	3.0	540	650	710	1000
4	4.0	560	690	740	1070
5	6.0	—	710	—	—
6	8.0	—	—	—	—

T/D	N_c
2.50	520
2.76	630
3.18	680
4.26	980

Run 2　　　　　　　　　D　　　= 6.37 cm

S.No.	Particle-Concentration %	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.07 cm	T= 16.2 cm	T= 21.7 cm
1	1.0	350	400	430	630
2	2.0	380	440	480	700
3	3.0	400	460	510	740
4	4.0	410	480	530	770
5	6.0	440	490	540	800
6	8.0	–	–	–	–

T/D	N_c
1.99	410
2.19	440
2.53	460
3.39	700

Run 3　　　　　　　　　D　　　= 7.65 cm

S.No.	Particle-Concentration %	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.07 cm	T= 16.2 cm	T= 21.7 cm
1	1.0	240	280	310	480
2	2.0	270	300	330	500
3	3.0	280	320	350	530
4	4.0	290	330	370	550
5	6.0	300	350	390	580
6	8.0	320	–	410	600

Run 2   D   = 6.37 cm

S.No.	Particle Concentration %	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.07 cm	T= 16.2 cm	T= 21.7 cm
1	1.0	350	400	420	620
2	2.0	380	430	460	690
3	3.0	400	450	500	740
4	4.0	420	480	530	760
5	6.0	440	500	550	820
6	8.0	450	510	570	840

Run 2   D   = 6.75 cm

1	1.0	230	280	310	480
2	2.0	270	310	330	500
3	3.0	280	330	340	530
4	4.0	290	340	370	540
5	6.0	300	350	390	570
6	8.0	320	360	400	600

TABLE-10

N_c-values observed visually as well as by light scattering technique for propeller at various distances from the tank bottom.

T/H   = 1.5

Particle Concentration = 2.0%

No. of Buffles   = 4

Width of Baffles   = 0.1T

Propeller diameter   = 6.0 cm

S.No.	Clearance in cm	N_c (r.p.m.)			
		T= 12.75 cm	T= 14.07 cm	T= 16.2 cm	T= 21.7 cm
1	0.5	420	–	–	–
2	1.0	430	550	630	730
3	1.5	450	550	640	730
4	2.0	490	560	640	730
5	2.5	540	–	–	–
6	3.0	580	650	700	800
7	4.0	590	750	820	920
8	5.0	–	770	840	950

TABLE-11

N_c-values observed visually as well as by light-scattering technique for paddle impeller at various distances from the tank bottom.

T/H	= 1.5
Particle Concentration	= 2.0%
No. of Baffles	= 4
Width of Baffles	= 0.1T
Impeller diameter	= 5.1 cm

S.No.	Clearance in cm	N_c (r.p.m.)			
		T=12.75 cm	T=14.07 cm	T=16.2 cm	T= 21.7 cm
1	1.0	540	620	680	900
2	1.5	540	620	680	—
3	2.0	560	660	—	920
4	2.5	620	—	760	—
5	3.0	670	780	820	1020
6	3.5	—	800	—	—
7	4.0	—	—	900	1140
8	4.5	—	—	910	1190
9	5.0	—	—	—	1210